# Development of Brittleness Index based on Shear Strength Parameters of Heat Treated Rock

*Project report submitted to*
*Visvesvaraya National Institute of Technology Nagpur,*
*In partial fulfillment of the requirements for the award of the degree*

## Master of Technology
## in
## Excavation Engineering

by

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**2025**

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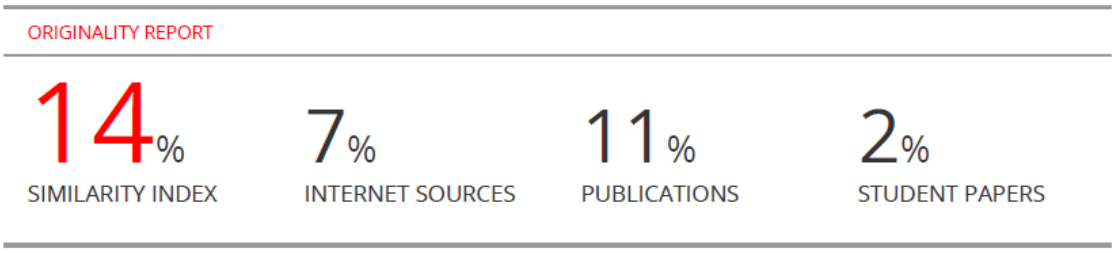


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# ABSTRACT

Brittleness is a very important mechanical property of rock, which defines how a rock would fail by controlling the response of rock in reaction to applied external load. The loss of load bearing capacity post peak stress is a significant feature of brittle rocks. There are numerous definitions of brittleness e.g., loss of internal cohesion, absence of ductility, sudden loss in load bearing capacity, material having very little plastic deformation etc., but there is no universally accepted definition of brittleness. Several factors affect brittleness e.g., temperature, confining pressure, porosity, total organic content, texture and weathering of rock etc. In order to express the brittleness of rock quantitatively many brittleness indices were developed in the past. These brittleness indices find applications in different areas like excavation, shale gas extraction and underground nuclear repository etc. These indices are dependent on different parameters e.g., strength, elastic, mineralogical composition, stress strain curves. However most of the indices were developed based on only strength and elastic parameters and indices based on shear strength parameter were inadequate, therefore in this study, an attempt was made to develop a new brittleness index of Chunar sandstone based on its cohesion and angle of internal friction. Furthermore, the effect of heat treatment of rock on developed brittleness index was also analysed. For that, physico-mechanical properties i.e. uniaxial compressive strength, Brazilian tensile strength, density, $V_p$, $V_s$, porosity, cohesion and angle of internal friction of Chunar sandstone were evaluated at temperature range of 25°C, 200°C, 300°C,400°C, 500°C and 600°C. It was observed that the density, porosity, $V_p$, $V_s$ were found to decrease with increasing temperature. Similarly, the uniaxial compressive strength was maximum at 200°C and thereafter decreased, The Brazilian tensile strength was highest at 400°C and thereafter decreased. The cohesion increased at 200°C and thereafter decreased whereas angle of internal friction exhibited the opposite trend with values initially decreasing till 200°C and thereafter increasing. The proposed brittleness index showed good correlations with angle of internal friction, cohesion, UCS and existing brittleness indices $B_1$, $B_2$ and $B_3$. The values of $R^2$ were 0.91, 0.91, 0.91 for $B_1$, $B_2$, $B_3$ and 0.92, 0.99, 0.99 for UCS, cohesion and angle of internal friction respectively. The developed brittleness index first increased till 200°C and thereafter decreased with increasing temperature.

**Keywords**: Brittleness, Brittleness index, Drillability, Rockburst, Shear strength parameters

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# CHAPTER 1
# INTRODUCTION

## 1.1 Background

With the rise in consumption and demand of minerals and exhaustion of shallow depth deposits, mining at higher depth became a necessity. But greater depth means more temperature and stress along with hard rocks, displaying abnormal behaviour. When we apply load onto rock, different rocks would react differently to that. Their reaction depends on a number of factors like mineralogical composition, state of stress, strength of rock etc. There exists a category of rocks, based on how they react to load, within which the rocks do not deform plastically, but develop sudden loss in internal strength because of development of a network of internal cracks, such rocks are called brittle rocks and phenomenon is called brittleness. A typical stress strain curve is shown in figure 1.1 .

Brittleness is one amongst the most important properties associated with geomaterials as per Hao et al. (2019). Brittleness is also one of the most crucial research topic in the field of rock engineering as per Tirayaki (2006).Brittleness reflects mechanical behaviour and failure Characteristics of rocks under different Loading as well as unloading conditions as per Meng et al. (2020). brittleness is expressed in the form of brittleness index and found application in different fields of engineering like civil, mining, petroleum etc. Brittleness can be used for prediction of the drilling performance of TBM as per Hao et al. (2019), extraction of shale gas as per Ye et al. (2020), construction of underground nuclear repository as per Ali et al. (2022), study of rockburst as per Cai et al. (2015), underground storage of $CO_2$ , studying cuttability as per Dursun and Gokay (2015), studying drillability as per Yarali and Soyer (2011), computing specific energy as per Altindag (2003), stability assessment of rock as per Meng et al. (2020). Brittleness is a very important mechanical property of rock, because it determines how the rock would deform when subjected to stress. Plasticity means that a material would deform without forming cracks , but a brittle material would develop cracks with very little deformation. It is a term used in rock engineering to define how the rock would fail as per Zhang et al. (2016). Ai et al. (2016) defines brittleness as ability to absorb energy in the pre peak stage and the ability of fracture to be self sustaining in the post peak stage.

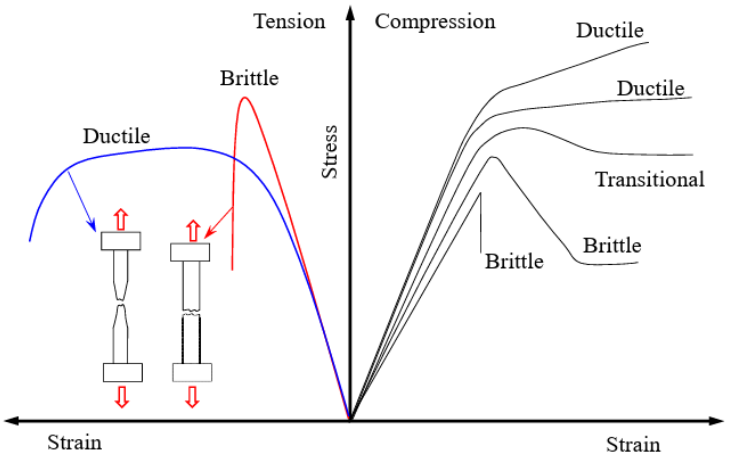


**Figure 1.1** A typical stress strain curve as per (Meng et al., 2010)

Brittleness, on the other hand, is the ability of a material to resist permanent (or inelastic) deformation as per Ye et al. (2020). Brittle materials have high resistance to deformation and less resistance to fracturing as per Lie et al. (2023).Permanent deformation represents material failure. When the material changes from the elastic stage to the plastic stage, the material is subjected to failure. For brittle failure this period of plastic deformation is short and brief. If the period of plastic deformation is long, then material might be subjected to ductile failure.

Till now many different researchers tried to define brittleness but no universally accepted definition of brittleness exists as per Zhang et al. (2004) .Hetényi (1950) defined it as lack of ductility. Ramsay (1968) defined it in terms of loss of cohesion. Howell (1960) defined it in terms of deformation by stating that brittle materials have very little plastic deformation. Obert and Duvall (1967) stated that a material like cast iron or any rock can be defined as brittle if it terminates at stress slightly beyond the yield stress as per Tirayaki (2006). Ye et al. (2020) stated brittleness as a combined effect of rock's mechanical properties. Li et al. (2023) Defines brittleness as occurrence of failure at or above yield stress. Rapid loss in bearing capacity of rock upon generation of plastic deformation as per Xu et al. (2022). Ability to fracture without appreciable plastic deformation as per Andreev (1995). Ease of crack propagation as per Lawn and Marshall (1979).

It is basically a behaviour of rock wherein rocks absorb huge amounts of energy and release the same in very small instances of time, since hard rocks have the ability to resist load they display this sort of behaviour.

However there is no consensus yet on the definition of brittleness, mainly because it comes under different fields of engineering and researchers from different fields tried to define it from their own perspective based on their experiences. Researchers have considered various different parameters to study brittleness like strength parameters, elastic parameters , mineralogical composition etc.

## 1.2 Understanding brittleness index

Now in order to express brittleness quantitatively various indices are developed these are termed as brittleness indices. These indices engage various different parameters like strength parameters, elastic parameters, stress strain curve, mineral composition , well logging data , penetration test , indentation test as per Meng et al. (2020).These indices are used in different fields of engineering like mining, civil etc. These indices developed for one particular field are not applicable for other fields, maybe because the data upon which these indices are based may be specific to that particular industry like for example strength parameters are considered important for rockburst whereas mineral composition and porosity is important in shale gas extraction. As a result different fields of engineering developed different indices specific to that field. These brittleness indices are based on different principles, somewhere it is based on the concept of energy accumulation and storage and somewhere the shape of stress strain curve. Different researchers adopt different approach towards computing these indices some of these are as follows:

- By conducting various tests in the laboratory and obtaining data from it.
- Performing regression analysis or computer algorithms on them to gain insight from data.
- Using data from other researchers to generate correlations and plot
- Conducting tests on site and generating data like in well logging, and using software to analyse the data.
- Making use of already existing brittleness indices to compare values with it.
- Algorithms can be developed to generate numerical simulation datasets, which can be fed into machine learning models.
- Brittleness index can also be generated by combining other indices.

All these attempts are made because of the importance of brittleness in different areas of engineering.

It was observed that brittle rocks show sudden strength drop post failure, that means their strength drops tremendously once the rock fails. Zhang et al. (2004) stated some characteristics of brittle rocks are as follows as

1)less elongation developed when load is applied

2) Different fractures surfaces are visible

3) More finer particles and crack generation under application of load

4)High compressive strength to tensile strength ratio

5) Higher angle of internal friction

6)Higher resilience

7)Higher Young's modulus and lower Poisson's ratio.

8) Sudden drop in strength post failure

9) Presence of brittle minerals like quartz

10) Brittle materials fails suddenly

It is important to have an understanding of all these topics as they are used for computing the brittle indices. Proper understanding of brittleness is very important as it finds application in various fields like shale gas extraction, underground nuclear repository, rock burst, hard rock mining, geothermal energy extraction. Brittleness affects cracks initiation and expansion, spalling of rocks, and helps to study the deformation characteristics of rocks as per Li et al. (2024).

## 1.3 Importance of developing brittleness index

We quantify a substance based on a certain value. For the same things different people may express different values. Such as despite discussing the same things, no consensus can be achieved. This is because things are expressed qualitatively and judged from one's scale based on perspective. Similar was the case with brittleness, to solve this issue, brittleness indices were developed through which values of brittleness were expressed quantitatively. Now one can get to know whether the rock is brittle, if yes, then how much?, and how we arrived at that value ?; Through brittleness indices different factors affecting brittleness and extent by which they affect can be understood. Also with the help of brittleness index it becomes possible to

express the values of brittleness in qualitative form which makes it easier to understand. Severity of brittleness can be understood based on the criteria developed relevant to particular index and associated values with range and description. Brittleness indices are incorporated into various rockburst prediction models including empirical, numerical, and statistical methods, to assess rock stability and predict rockburst potential.

## 1.4 Motivation

Although there are a number of brittleness indices developed till date, the number of indices based on shear strength parameters were found to be highly inadequate, most of the indices focussed extensively on the strength parameters, elastic parameters, mineral composition and on stress strain curve. However cohesion and angle of internal friction have a role to play in imparting strength to the rocks. As per the literature review there, no index was found based solely on parameters like cohesion. Pressure and temperature have huge role to play in phenomenon such as rockburst which is again a brittle failure of rock, similarly temperature plays a huge role in different application areas of brittleness like drillability and underground nuclear waste storage, stating the role of temperature. Therefore an attempt was made to develop a new brittleness index based on shear strength parameters along with variation with temperature.

## 1.5 Objectives

The objectives of the study are followings

1. To review various existing models of brittleness index.
2. To carry out physico-mechanical characterization of Chunar sandstone before and after heat treatment.
3. To develop a brittleness Index based on the shear strength parameters of heat treated rock.

## 1.6 Thesis outline

The outline of the thesis is titled as “Development of Brittleness Index based on Shear Strength Parameters of Heat Treated Rock”. It includes 5 chapters and its outline is as follows

CHAPTER 1:

This chapter is based on development of understanding on brittleness and brittleness index, along with their applications, the objective for performing the work along with the motivation and outline of the thesis.

CHAPTER 2:

This chapter deals with extensive literature review of the topic. It includes brittleness indices, the factors affecting the brittleness and different areas of applications of brittleness like drillability, underground nuclear waste storage along with that the variety of brittleness indices developed are also mentioned.

CHAPTER 3:

This chapter discuss the methodology associated with development of the brittleness index. The various tests carried out on rock are mentioned.

CHAPTER 4:

This chapter deals with the result of the study obtained by performing different tests on rock.

CHAPTER 5:

This chapter summarizes the main findings of the study and suggests future work.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Brittleness indices

Brittleness index is basically an expression comprising parameters which are said to be associated with brittleness. These are developed to express brittleness of rocks in terms of some specific values such that one can get to know how high or low the brittleness of rocks is. It helps to develop a rating system for expressing brittleness of rocks. There are a variety of brittleness indices available but most of these are very specific in nature , that means that these found applications in certain specific fields as the input parameters taken into considerations are specific to those fields. For example, consider the case of shale gas extraction wherein neutron porosity is considered for developing index or consider the case of rock burst where mechanical properties are considered, so these parameters are specific to those fields. Brittle indices founds applications like Predicting rockburst, drillability, cutability, penetrability, shale gas extraction, $Co_2$ geosequestration, underground nuclear repository, selection of mechanical excavators, stability of excavation, safety of excavation, design of excavation as per Li et al. (2023).

These indices are as many as 80 in number according to Meng et al. (2020). But all these indices are not equally useful, some of them find a lot of applications but some find applications in specific fields. Parameters like drilling rate index (DRI) are based on brittleness index, specific energy which can be defined as energy required to cut and produce a unit volume of rock can be computed through brittleness index. A lot of these indices are based on the parameters which can be easily obtained in the laboratory, consider the Strength parameters, they can be easily obtained in the laboratory, that can explain why there are so many indices based on them, also the stress strain curves, mineralogical composition, elastic parameters can also be obtained via simple terms in the laboratory. But some required performing tests on the site, like shale gas extraction involves collection of data on site, they are termed as well logs, offering data about the lithology of the site using which one can get to know about brittle and non brittle formation. The neutron porosity technique used for obtaining the brittleness index is something which is specific to that field. Some of these indices are based on simple arithmetical operations on parameters while others involve complex mathematical functions. Mostly these indices are results of regression analysis, obtaining data and thereafter applying regression analysis onto them and obtaining the required equations. Some equations are based on single parameters

while some involve multiple parameters. The brittleness index is actually made for expressing the brittleness of rock but sometimes they merely act as representative of the strength of rock. The brittleness index developed can also be correlated with other index or other parameters based on requirement. Sometimes the limitations of one index act as a catalyst for generating another index.

Brittleness indices consider variety of parameters,as per Meng et al. (2020) these are as follows

1. Strength parameters
2. Compression stress strain Curve
3. Elastic parameters
4. Mineral composition
5. Conventional well logging data
6. Angle of internal friction
7. Force penetration graph
8. Indentation test
9. Content of fines post impact
10. Over consolidation characteristics

Advantages of brittleness indices are as follows

1. Improves understanding on the impact of various parameters in the overall brittleness of rock.
2. Knowing brittleness can help in planning of excavation, selection of equipment for excavation and identification of particular areas which exhibits threat to excavation
3. Ease of communicating severity of brittleness
4. Founds application indifferent fields of Engineering like mining, civil, oill and gas industry etc.
5. Helpful in studying the failure process of rocks.
6. Simple laboratory test can help us compute the brittleness of rock.
7. Brittleness indices are incorporated into various rockburst prediction models including empirical, numerical, and statistical methods, to assess rock stability and predict rockburst potential.

Limitations of brittleness index are as follows

1. Majority of brittleness indices developed till date are not of much use.
2. Indexes made for one field are not applicable in other fields.
3. Rocks having strong grains are bound to have higher strength so these two things are interrelated, still they are placed in different indices
4. In case of brittleness index based on mineralogical composition, all brittle mineral are considered to impart equal brittleness in overall brittleness of rock, this is not necessary, as like hard mineral and not so hard mineral based on Mohr scale of hardness cannot impart equal level of brittleness to rock.
5. If some minerals Increase the brittleness then some should decrease it as well. Then these minerals should be offered with a negative coefficient in the formulas to express their reduction tendency but that is not performed so.

## 2.2 Discussion on brittleness indices based on different parameters

### 2.2.1 Brittleness index based on strength parameters

Development of brittleness indices started post 1967. Since then as many as 80 indices were developed which are summarised by Meng et al. (2019). Strength can be defined as ability to resist load. strength parameters namely compressive and tensile strength are made use of for development of brittleness index since these tests can be easily conducted in laboratory. Hucka and Das (1974) was the pioneer in the development of brittleness index, $B_1$ was the earliest developed brittleness index and it was basically the ratio of the of brittleness index for predicting rock burst. Kahraman (2001) studied the interrelationship between brittleness index and penetration rate of tunnel boring machine as shown in Fig 2.1, it can be observed that as the brittleness index increases, penetration rate decreases. It's evident as more brittle rock would demand higher energy to generate cracks, if that amount of energy is not provided rocks would not fail and thus we won’t be able to penetrate further within the rock.

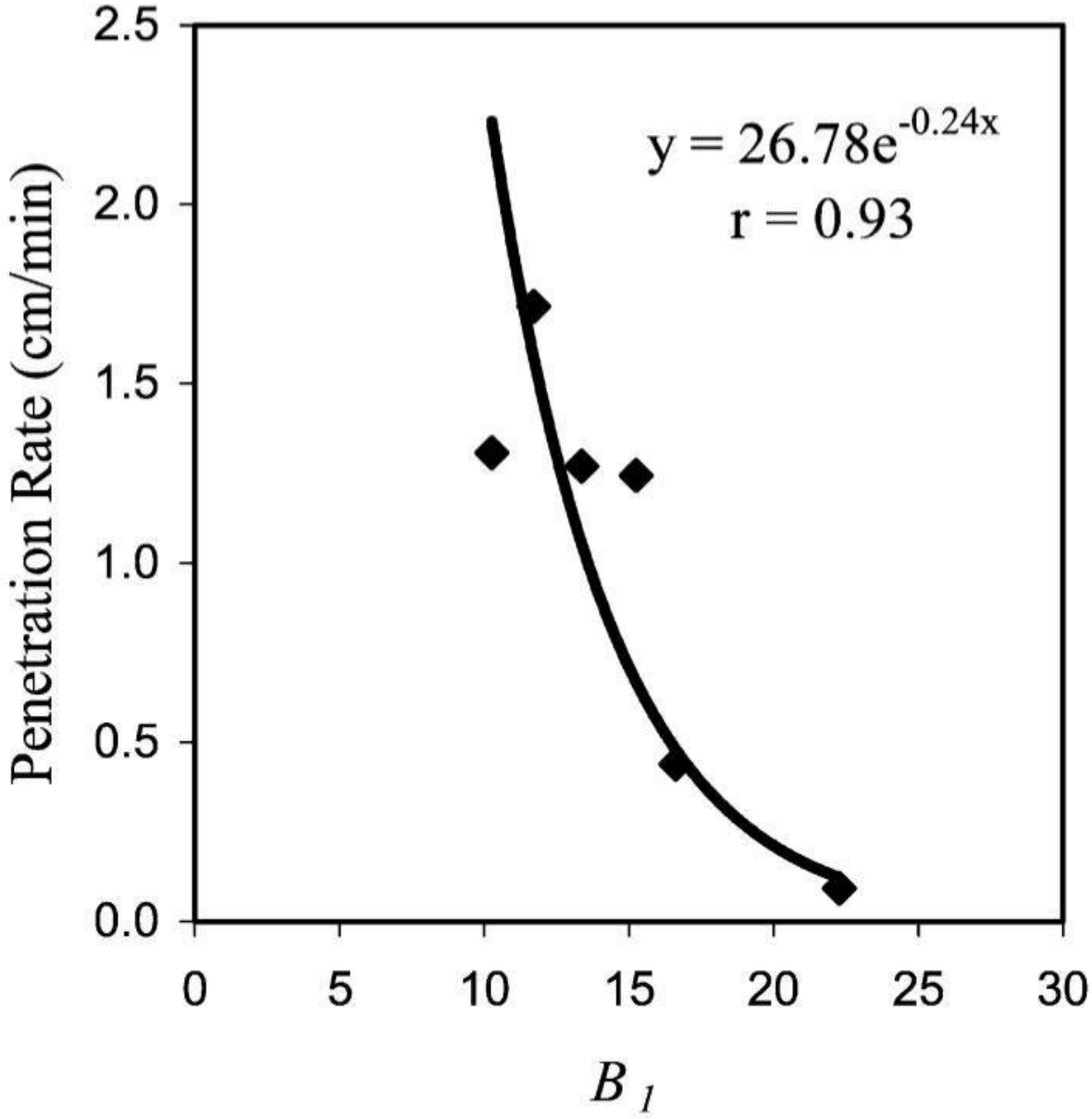


**Figure 2.1** Interrelationship between penetration rate and brittleness index $B_1$ as per (Kahraman, 2001)

Meng et al., (2021) pointed out some drawbacks of index $B_1$ like, like its inability to express the rock fracture process, acting merely as an indicator of rock strength and narrow range expressed by the index. Like two different rocks having a variable range of strengths can have the same ratio and thus the same $B_1$.

$B_2$ is based upon certain modifications on $B_1$ and was developed by Hucka and Das (1974), higher value of $B_2$ indicates more brittle rock. Certain Researchers tried to correlate $B_2$ with other parameters like cuttability, boreability and drillability. Gong and Zhao, (2007) reported negative correlation between $B_2$ and boreability of rock. This section includes the brittleness

indices based which considers strength parameters as input parameters. The strength of rock means resistance against stress. Strength parameters come under Mechanical properties of rock which includes uniaxial compressive strength, Brazilian Tensile strength and Shear Strength. Since all these can be determined in the laboratory therefore there are many indices based on them. Table 2.1 states different indices based strength parameters

**Table 2.1** Brittleness index based on strength parameters

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| $B_1=\sigma_c/\sigma_t$ | $\sigma_c$ is compressive strength; $\sigma_t$ is tensile strength | This was the earliest developed brittleness index based solely on strength parameters which can be easily obtained from the laboratory. The higher value of the index reflects more brittle rock, but the narrow range is a disadvantage as different combinations of strength parameters can generate identical values for the index. | Hucka and Das (1974) |
| $B_2=(\sigma_c-\sigma_t)/(\sigma_c+\sigma_t)$ | | It was observed that the difference between the compressive and the tensile strengths was high. In case of brittle rock and low in case of non- brittle rock. That means as the difference increases so does the brittleness of rock as well. Therefore, this fact was used to measure brittleness. It has the same disadvantage as the previous one. moreover these indices do not consider the confining pressure as per Wang et al. (2023) | Hucka and Das (1974) |
| $B_3=(\sigma_c+\sigma_t)/2$ | | Different brittleness indices were discussed. Drilling rate index was correlated with different brittleness indices. Here $B_8$ was | Özfırat et al. (2016) |

| | | | |
|---|---|---|---|
| | | represented by ($\sigma_c\sigma_t/2$) whereas $B_{10}$ by ( $\sigma_c+\sigma_t)/2$ i.e. the brittleness index proposed by the researcher. Good correlation was obtained between $B_8$ and $B_{10}$. Correlation coefficient (R) is found to be 0.84 between compressive strength and drilling rate index and the same in case of tensile strength is 0.78. | |
| $B_4=(\sigma_c\sigma_t)/2$ | | The aim of the study was to correlate brittleness and specific energy of rock. Since specific energy is a measure of cutting efficiency of rock. Specific energy was correlated with brittleness indices $B_1$ and $B_2$ but no correlation was obtained and when specific energy was correlated the index developed by author good correlation was obtained. Therefore application of index would be helpful in defining cutting efficiency. | Altindag (2003) |
| $\sqrt{(}\sigma_c\sigma_t)/2$ | | The index is used for computing rock fragmentation efficiency. The index is more of an indicator of strength rather than brittleness of rock. Also the narrow range of values of $\sigma_c$,$\sigma_t$<br>Offers identical values of index for different combinations of strength parameters values. | Altindag (2010) |
| $0.198\sigma_c - 2.174\sigma_t + 0.913\rho - 3.807$ | $\sigma_c$ is Compressive strength, $\sigma_t$ is tensile strength and $\rho$ is density | The index was developed with the aim to directly measure brittleness of rock. Punch penetration test was carried out and relationship between brittleness index and intact properties of rock was studied. The | Yagiz (2009) |

| | | | |
|---|---|---|---|
| | | developed brittleness index was correlated with strength parameters and good correlation was obtained in between them. Since the developed index was developed as a function of rock characterization it's better than other indices which are solely based on strength parameters. | |
| $\sigma_t^{0.84}E^{0.51}\sigma_c^{-0.21}$ | E represents Young's Modulus | The proposed index was used for predicting fracture toughness of rock. Fracture toughness which is denoted by K can be defined as resistance to propagation of cracks.<br>Fracture toughness is of three Classes ie type 1,2 and 3.<br>The correlation coefficients between brittleness index and fracture toughness of class 1 and class 2 was<br>0.68 and 0.79, respectively, which Was higher than<br>The already-existing strength-based indices. | Nejati and Moosavi (2017) |
| $0.002\sigma_c - 0.490\sigma_t - 4.939PLS + 91.179$ | PLS represents point load strength | Thorough review of concepts of cuttability ,brittleness of rocks and different brittleness indices. Samples were subjected to different mechanics test and using rock cutting test specific energy was also determined. brittleness test was carried out using a method suggested by Dahl (2003), thereafter using multiple regression analysis brittleness index was developed. | Dursun and Gokay (2015). |

### 2.2.2 Brittleness index based on stress strain curve

Stress strain curve can be used to determine the strength parameters of rocks as per Wang et al. (2023).the parameters obtained from stress strain curves are useful for studying rock failure process as per Gao et al. (2022)

Both pre peak and post peak parts are taken into consideration. therefore the difference in between the strength parameters pre peak and post peak can be computed. which can further be used for determining the brittleness of the rock. Also the shape of the stress strain curve itself helps us to determine whether rock is brittle or not. Researchers have developed many indices based on the stress strain curves. Various different parameters are obtained from the curve and used as an input for computing brittleness indices. the brittleness indices based on stress strain curves are shown in table 2.2

**Table 2.2** Brittleness index based on stress strain curve

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| $\varepsilon_e/\varepsilon_p$ | $\varepsilon_e$, $\varepsilon_p$ represents elastic strain and total strain at failure | Higher the ratio more would be the brittleness of rock. reversible strain to the strain wherein the material will recover original shape once the external force which causes the deformation is removed. total strain is the sum of reversible and irreversible strain. | Zhang et al. (2014) |
| $\varepsilon_{li}*100$ | $\varepsilon_{li}$ represents the absolute irreversible strain at failure | When load is applied on rock and plastic deformation occurs then that can be used to determine the brittleness . The categorization was carried out based on the value of brittleness index as brittle rocks have $\varepsilon_{li}< 3\%$, ductile rocks have $\varepsilon_{li}>5\%$ and rocks in the Brittle-Ductile transition stage have $3\%< \varepsilon_{li}< 5\%$. | Andreev (1995) |

| | | | |
|---|---|---|---|
| $(\tau_p-\tau_r)/\ \tau_p$ | $\tau_p$ is the peak shear strength and $\tau_r$ is the residual shear strength. | The index was built based on different possible failures that can occur in brittle and ductile rock when load is applied on them. when load is applied on brittle rocks there by fail with sudden loss in shear strength whereas ductile rocks do not show instantaneous reduction in shear strength | Bishop (1967) |
| $1/\varepsilon_e$ | | Smaller value of elastic strain represents higher values of brittleness of rock. | Gong and Sun (2015) |
| BI= $\sigma_c/\varepsilon_p$ | $\boldsymbol{\sigma}_c$ represents compressive strength of rock | Five different grades of brittleness were developed based on values of brittleness index which were extreme brittleness (BI > 40), High brittleness (30 < BI < 40), brittle (20 < BI < 30), middle brittleness (10 < BI < 20) and low brittleness (BI < 10). | Liang et al. (2017) |

### 2.2.3 Brittleness index based on force penetration graph

Yagiz (2008) developed a brittleness index based on force penetration test for this, samples were collected from around 48 different tunneling sites around the world ,Thereafter samples were prepared and uniaxial compressive strength test and tensile strength test were carried out on samples. Punch penetration test was used for estimating the normal load on disc cutter to calculate brittleness of rock. A computerized data acquisition system continuously records force–penetration data during the test brittleness index =$F_{max}$ /P where $F_{max}$ is maximum applied force on a rock sample in kN, P is the corresponding penetration at maximum force in mm.The plot is shown in figure 2.2. The visuals of plot for soft and plastic rock is shown in figure 2.3. The nomenclature for understanding them is shown in figure 2.4

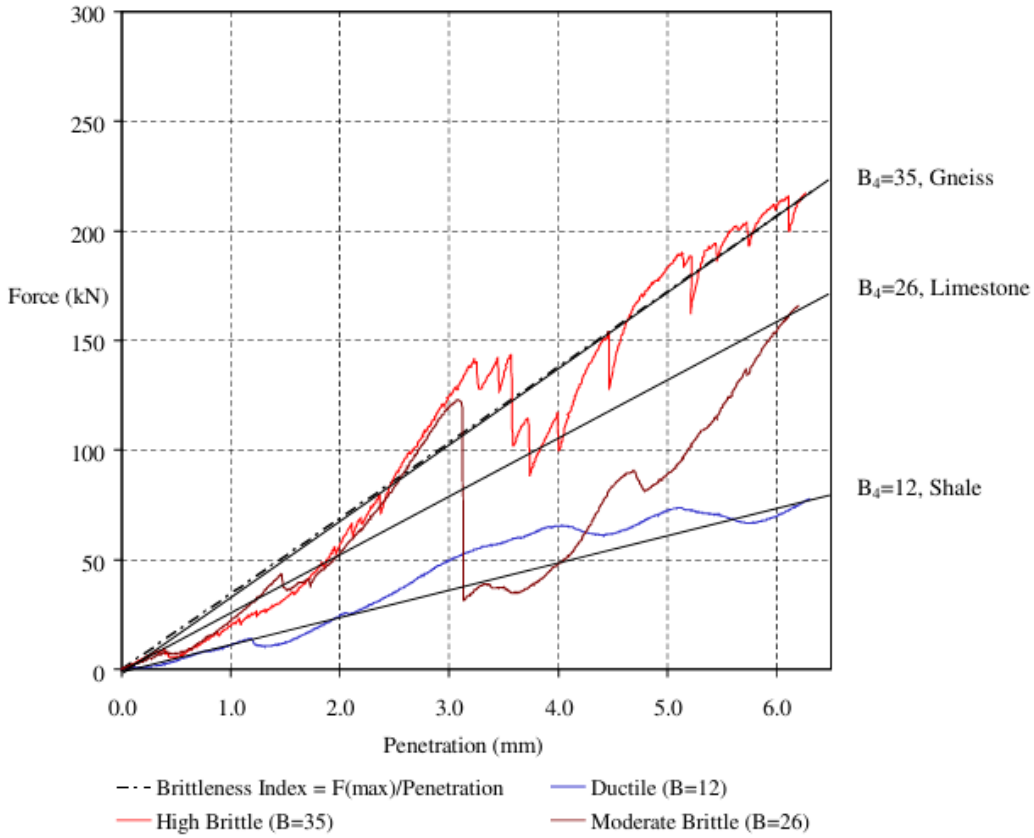


**Figure 2.2** Plot of force and penetration corresponding to different rocks as per (Yagiz, 2008)

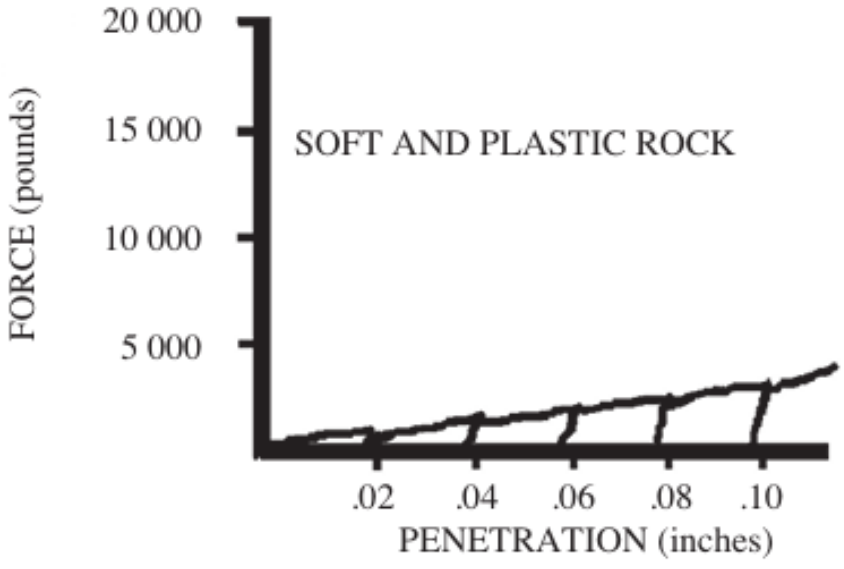


**Figure 2.3** Visual classification of brittleness based on force penetration graph as per (Copur et al., 2003)

Brittleness index displaying the brittleness of rock can characterize the rock brittleness together with density, type and strength of rocks through visual inspection of the force–penetration graph.

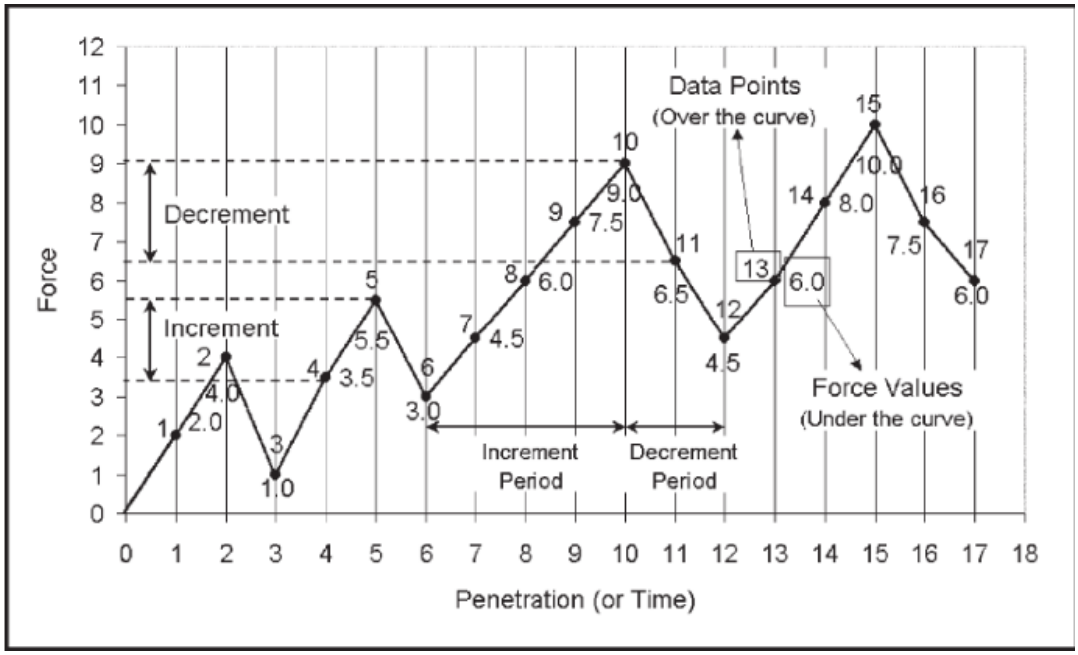


**Figure 2.4** Nomenclature for force increment and decrement rates and periods of force penetration graph as per (Copur et al., 2003)

Brittleness indices make use of force increment and decrement period for computing brittleness index. These indices developed were used for computing fragmentation efficiency as per Copur et al. (2003). Different brittleness indices based on force penetration graph is shown in table 2.3 .

**Table 2.3** Brittleness index based on force penetration graph

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| $F_{max}$= P | Here $F_{Max}$ means maximum force and P means penetration depth at maximum force | Samples were collected from different tunneling sites around the world thereafter sample preparation was carried out. Followed by testing of samples including Uniaxial compressive strength test and Brazilian tensile strength tests thereafter calculated brittleness index with help of punch penetration tests thereafter statistical evaluation of data was carried out followed by creation of model for which the commercial software packages were utilized to carry out multiple linear regression analysis between rock properties and the measure rock brittleness and establishing correlation between parameters. The | Yagiz (2009) |

| | | | |
|---|---|---|---|
| | | developed index was found to be positively correlated with brittleness indices $B_1$ and $B_2$ also We can characterize the rock brittleness together with density, type and strength of rocks with visual inspection of the force–penetration graph. However, conducting a punch penetration test is expensive | |
| $P_{dec}/P_{inc}$ | $P_{inc}$ and $P_{dec}$ are the average force decrement period and increment period expressed in seconds respectively | Basic parameters considered for development of brittleness index are force increment and decrement rates, force increment and decrement periods, and number of increment and decrement data points. Uniaxial compressive strength, Brazilian tensile strength and dynamic elasticity modulus (acoustic velocity) tests were performed. The shape of force penetration Graph was considered to determine the type of rock. Ductile rocks displayed Flatter force-penetration graphs , for more brittle we obtained a more fluctuated force-penetration graph . Also in case of brittle rock, a material more prone to breakage, we have short increment period whereas for a Ductile material increment period would be longer , these increment and decrement periods Changes based on the size of the chips, cracks and crushed zone Along With the violence With which breakage occurs for example Larger chips and Disturbance of the crushed zone due to violence Of the chipping might increase the decrement periods. Average Force increment rate is computed by subtracting consecutive points in the force penetration Graph and adding them followed by average of these values. The number of sequential force increment points up to a decrement point is defined as a force increment period ($P_{incp}$), The average force increment period ($P_{inc}$) similarly The average force decrement period is ($P_{dec}$), the ratio of decrement to increment period is termed as brittleness index. Whereas the ratio of summation of values of increment and decrement period is termed as force index (FI). The values of these indices lie between 0 and 1, Lower FI and BI signifies. This index is Moderately correlated with cutting performance and rock mechanical properties and poorly correlated with coarseness index and cutting size distribution: More Brittle rock. brittleness index developed can be used for predicting cutting efficiency as well as mechanical properties of rocks. | Copur et al. (2003) |

### 2.2.4 Brittleness index based on Mohr envelope

The Mohr envelope is a linear line obtained from the plot of normal stress and shear stress. It is derived from Mohr coulomb's failure criteria, according to which a material fails when a critical combination of normal stress and shear stress is achieved. Cohesion and angle of internal friction are the different parameters present in this criteria therefore one of the two can be made use of in determining the brittleness index. The Mohr envelope can be plotted by obtaining data from the triaxial test. The brittleness indices are shown in table 2.4 .

**Table 2.4** Brittleness index based on Mohr envelope

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| Sin(ϕ) | ϕ represent angle of internal friction | The rate of rise in shear stress accompanied by increase in confining pressure is a characteristic of brittle rocks. This was the main idea behind developing this brittleness index. Ductile rocks were found to have lower angle of internal friction. The method had an added advantage that brittleness can be determined at any stage. | Hucka and Das (1974) |
| ϕ=45°-2$\alpha$ | $\alpha$ represents fracture angle of specimen at different confining pressure | No application was stated. | Hucka and Das (1974 |

### 2.2.5 Brittleness index based on conventional well logging

Conventional well logging is the process wherein the data obtained from a borehole is analysed with the aim to get information about geological formations around the borehole. This concept is of much importance in oil and gas industries, Also in shale gas extraction, where brittleness of reservoir rock governs sweet spot for features. There are indices based on the data obtained from well logging, few of them are shown in table 2.5 .

**Table 2.5** Brittleness indices based on conventional well logging

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| $\int_{r=R}^{+\infty}(\Delta V_{\mathrm{P}}(r)/V_{\mathrm{p}}\mathrm{d}r)/R$ <br> $\int_{r=R}^{+\infty}(\Delta V_{\mathrm{S}}(r)/V_{\mathrm{S}}\mathrm{d}r)/R$ | Integration of the radial variation profile (DVP, DVS) | Brittleness index was calculated based on elastic wave velocity. Variations in compressional and shear wave velocity around the borehole was considered to examine brittleness of rock around the borehole. P-wave travel-time tomography Along with Radial shear-wave dispersion inversion techniques were used for this purpose. The index was proposed on the idea that , whenever drilling is carried out, microcracks are generated around the borehole, the generation and propagation of cracks depends on brittleness of surrounding rock. Now since cracks are developed the elastic wave velocity of rock would decrease and this change in velocity is the major factor. The velocity change reflects the effect of brittleness. | Tang et al. (2016) |

### 2.2.6 Brittleness index based on elastic parameters

Elastic properties of rocks provide information of how the rock responds to stress and strain. Young's modulus and Poisson's ratio are the most common elastic properties considered for computing brittleness as per Wang et al. (2023). brittleness is correlated with the plastic as well as elastic deformation according to Ye et al. (2020). Different elastic parameters include elastic modulus, Poisson's ratio, Bulk Modulus etc. they are of use in different industries like

Mining, Civil and Geotechnical engineering. Different brittleness indices based on elastic parameters are shown in table 2.6 .

**Table 2.6** Brittleness index based on elastic parameters

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| $0.5[(E-E_{min})/(E_{max}-E_{min})+(v-v_{max})/(v_{max}-v_{min})]$ | E represents Young's Modulus and v represents Poisson's ratio, subscript max and min represents their maximum and minimum values | Young's Modulus and Poisson's ratio are found to affect the brittleness of rock; these two relationships were combined together into one single relationship. This indicates that brittle rocks have the ability to convert absorbed energy into elastic energy that helps in extension of cracks as per Ye et al. (2020) . | Rickman et al. (2008) |
| E/v | | Higher values of Young's modulus and lower values of Poisson's ratio would correspond to a highly brittle rock. therefore higher the values of the index more would be the brittleness of rock | Luan et al. (2014 |
| $E\rho/v$ | here $\rho$ represents the density of rock | The index developed found application in the field of shale gas extraction. Higher values of density and lower the values of Poisson's ratio more would be the brittleness of rock and better would be the rock for hydraulic fracturing | Sun et al. (2013) |

| | | | |
|---|---|---|---|
| 50*(E-28v+10.2)/7 | | This index is mostly used in area of unconventional shale gas extraction. | Ye et al. (2022) |
| $(E_n+\mu_n)/2$ | $E_n$ represents normalised Young's Modulus and $\mu_n$ represents normalized Poisson's ratio | most widely used in oil field practices and was based on statistical results. the term normalized means that values are expressed with respect to some reference material | Lie et al. (2023) |

## 2.2.7 Brittleness index based on indentation test

Indentation is just like a cavity made in a substance by application of indenter. The main emphasis is on cracks generated like brittle material and ductile Material develops different amounts of cracks when subjected to indentation tests were blow frequency, compressive strength and quartz content. Kahraman et al. (2000) developed a drillability index based on force-penetration curves obtained from indentation tests and developed a mathematical penetration rate model specially for rotary drills using it and obtained good correlation with other mechanical properties of rocks like compressive strength, tensile strength, point load index, Schmidt hammer value, impact strength, p-wave velocity, elastic modulus and density. Martin (2006) discussed two types of indentation test , first one based on size of impression left by indenter which includes Brinell and Vickors hardness test . Second category measures depth of penetration by indenter which includes rockwell harden test . The various brittleness indices based on indentation tests are shown in table 2.7 .

**Table 2.7** Brittleness index based on indentation test

| **Brittleness index** | **Description** | **Understanding** | **Author** |
|---|---|---|---|
| $(H_\mu - H)/K$ | $H_\mu$ represents micro indentation hardness: H represents macro- | Macro Indentation was performed instead of Micro, wherein the name suggests the size of the indentor used. Macro Indentation hardness was found to be lower than Micro because of formation of more cracks in macro. Therefore the difference between macro and move | Hucka and Das (1974) |

| | | | |
|---|---|---|---|
| | indentation hardness: K is a constant. | hardness will represent brittleness and thus is considered in the formula. Despite this the Method is less Precise. this index is more applicable in drilling process | |
| $H/K_{IC}$ | H represent Hardness and $K_{IC}$ toughness | Hardness can be defined as resistance to deformation whereas toughness can be defined as resistance to fracture. The proposed brittleness index is based on indentation mechanics. As per which a material is susceptible to deformation in case of small scale loading and Failure in case of large scale loading. A universal deformation diagram was constructed using which mechanical response of any material whose hardness and toughness is known can be predicted | Lawn and Marshall (1979) |
| $HE/K_{IC}^2$ | | Discussed about relationship hardness and load , fracture. brittleness increases with increase in hardness and decreases with increase in fracture toughness. Hard material offers more resistance to indentation by indenter whereas high fracture toughness means more resistance to cracking . Variety of brittleness indices were discussed. | Quinn and Quinn (1997) |
| C/a | C represent crack length and a represent indent size corresponding to | Whenever a material is subjected to indentation with help of an indenter, cracks are generated. These cracks are clearly visible in case of brittle material. More cracks would be formed in brittle material than in ductile material. The | Sehgal et al. (1995) |

| | | |
|---|---|---|
| | Vickers Indent at the specified load | length of cracks formed can be measured and can be used in the predicting value of brittleness index. Vickers hardness test was used within which, hardness of material is determined by inserting diamond pyramid into the material. |

### 2.2.8 Brittleness index based on mineralogical composition of rock

Mineralogical composition of a rock is determined using X-Ray diffraction test. There are certain minerals which are classified as brittle minerals whose presence in the rock impart brittleness to the rock whereas the counterparts are the ductile minerals. The presence of ductile minerals suppresses the brittleness of rocks. The most important factor here is which minerals should be considered as brittle and which one as ductile. Also mineral composition alone would not be enough to categorize a rock as brittle, since factors such as porosity and grain size of minerals also affects the brittleness as per Luan et al. (2014). Similarly Zhang et al. (2014) mentioned that rock with identical mineral composition may have different brittleness values because of processes such as compaction. Ye et al. (2020) stated that different indices based on mineral composition offer same weight coefficients for all minerals meaning all of these minerals contribute equally to the brittleness of rock but that is not the case in reality. some of the brittleness indices based on mineral composition of rock are as shown in table 2.8.

**Table 2.8** Brittleness Index based on mineralogical composition of rock

| Brittleness index | Description | Understanding | Author |
|---|---|---|---|
| $W_Q/W_Q+W_C+W_{CL}$ | $W_Q$ represents weight of quartz; $W_C$ represents weight of carbonate ;$W_{CL}$ represents weight of clay | Brittle minerals like quartz contribute to the brittleness of rock whereas ductile minerals like clay suppress the brittleness of rocks. a higher value of the index would represent more brittle rock. This equation | Jarvie et al. (2007) |

| | | | |
|---|---|---|---|
| | | would give good results for formations containing higher amounts of quartz , clay and lower amount of carbonate content. But where we have a significant amount of carbonate content , this equation would give an underestimated value of brittleness. | |
| $W_Q+W_{DOL}/(W_Q+W_{DOL}+W_{LM}+W_{CL}+W_{TOC})$ | $W_{DOL}$ represents weight of dolomite and $W_{TOC}$ represents weight of total organic content; $W_{LM}$ represents weight of limestone | Quartz along with dolomite were considered as brittle minerals, whereas clay, limestone and total organic content were considered as ductile minerals. Therefore higher the numerator more would be the brittleness of rock and higher denominator would mean more ductile rock. This equation would - present accurate results for brittleness if dolomite is abundant in formations but if , | Wang and Gale (2009) |

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|---|---|---|---|
| | | calcite and dolomite both are abundant , this equation would underestimate the value of brittleness. | |
| $W_Q+W_F+W_C+W_P/W_{tot}$ | $W_Q$ represents weight fraction of quartz in % similarly , $W_F$ ,$W_C$ ,$W_P$ ,$W_{tot}$ represents weight fraction of feldspar, carbonate, pyrite, and total weight of all minerals the rock. | Quartz , feldspar, carbonate and [pyrite were considered as brittle minerals , based on the index , higher value would reflect higher brittleness. | Ye et al. (2020) |
| $W_Q+W_F+W_{mica}+W_{dol}/W_{tot}$ | $W_{mica}$ represents weight of mica | Herein mica was considered as a brittle mineral. Higher value of index would reflect higher brittleness. | Jin et al. (2014) |

### 2.3 Brittleness index based on other parameters

There are certain other parameters which are considered for development of brittleness indices, these are discussed in table 2.9 .

**Table 2.9** Brittleness index based on other parameters

| Brittleness index | Understanding | Category | Author |
|---|---|---|---|
| $S_{20}$ | It represents the percentage of fines less than 11.2 mm. Higher the portion of fines more would be the brittleness. Brittle rocks generates more fines and Ductile rocks | Content of fines | Dahl (2003) |

| | | | |
|---|---|---|---|
| | generate large fragments when subjected to failure. | | |
| $q\sigma_c$ | $\sigma_c$ represents the compressive strength of rock and represents the percentage of fines generated in the protodyakonov impact test. This index is a combination of strength parameters and fines content. . Higher the index more shall be the brittleness. | Content of fines | Hucka and Das (1974) |
| $UCS_{OC}/UCS_{NC}$ | $UCS_{OC}$ represents unconfined compressive strength at over consolidated state and $UCS_{NC}$ represents unconfined compressive strength at a normally consolidated state. | Over consolidation characteristics | Meng et al. (2020) |
| $\frac{\sigma_1-\sigma_3}{(2C\cos\phi+(\sigma_1+\sigma_3)\sin(\phi))}$ | This index was developed to overcome limitations in previous indices associated with the field of Hydraulic Fracturing. It takes into consideration principal stresses which was an unique feature of this index. Area of application is Hydraulic Fracturing . C represents Cohesion and $\sigma_1$, $\sigma_3$ represents principal stresses | Triaxial test | Lei et al. (2023) |
| $U^f/U_c^e$ | $U^f$ represents total strain energy at failure $U_c^e$ represents elastic strain energy consumed during the failure process. Plastic deformation consumes energy but brittle rocks experience very Little of the same. Higher the value of index more shall be the brittleness. | Method of Energy | Meng et al. (2020). |

## 2.4 Factors affecting brittleness of rock

Brittleness is a very important mechanical property of rock. It is affected by a variety of factors, some are external in nature like confining pressure, state of stress, and some are internal in nature like mineral composition, texture, structure. Not all factors equally affect the brittleness some affect more and some affect quite less than others. Therefore studying the factors affecting it is very important. Some of these factors are as follows

### 2.4.1 Temperature

Because of depletion of near earth deposits, mining has advanced to greater depth. But with increasing depth temperature rises, which is reflected by geothermal gradient. But this rise in temperature changes the physico-mechanical properties of rocks, which In turn controls how the rockmass would deform. As per Ye et al. (2022) temperature affects different rock mechanics properties such as strength characteristics, failure characteristics, rock deformation and brittleness. Temperature finds application in various fields like mining at greater depth, filling of nuclear waste in repositories, drilling at greater depth as per Wagner (2019). Fan et al. (2019) stated that high temperature causes changes in microstructure of rocks. Xu et al. (2010) discussed the relationship between porosity and temperature, where porosity was found to increase with increase in temperature.

The source of heat might also be the nuclear waste which is stored in underground nuclear repository, wherein the heat moves from waste into the surrounding rocks, in that case it becomes necessary to understand how the surrounding rocks would behave. Some scholars suggest that brittleness increases with increasing temperature whereas some suggest that it decreases with temperature. Studying temperature is important because brittleness is associated with phenomena such as rockburst, which are associated with rocks at greater depth and high temperature. If the effects of temperature on brittleness is known then it would be helpful to study and prevent rockburst because they cause loss of life and equipment. Yin et al. (2022) studied relationship between brittleness of granite and temperature and concluded that brittleness of granite decrease with increase in temperature, the importance of studying this relationship was also discussed, wherein the hypothetical case of fire in mine was considered and thereafter because of that how the surrounding rock will behave was considered. Yin et al. (2022) also summed up that the reason for decrease in brittleness of rock was energy dissipation which happened because of high temperature. From the figure 2.5 it can be observed that as

the temperature is increasing the energy dissipation index is also increasing and energy accumulation index is decreasing. At a temperature of around 200°C the energy accumulation and dissipation index have values of around 0.8 and 0.2 respectively whereas at temperature of 800° C the values of accumulation and dissipation index had values of around 0.4 and 0.7 respectively.

Wagner (2019) stated many reasons for studying the influence of temperature on rocks like deep mining, nuclear waste disposal etc. Temperature also has the ability to change the microstructure of rock by changing the minerals composition which has a weakening effect on rock as per Fan et al. (2018). From the figure 2.6 it can be seen that rise in temperature the brittle ductile transition is happening. The rock which behaves like a brittle rock at low temperature behaves like a ductile rock at high temperature. The steepness of the stress strain curve post yield stress helps us to differentiate between brittle and ductile rock. If the slope is too steep meaning sudden and rapid fall in stress generating a curve parallel to the stress axis indicates a brittle rock. Whereas a gradual continuation of curve post yield stress means a ductile rock. form the figure 2.5 we can observe that at low temperature the rock was brittle whereas at high temperature its ductile.

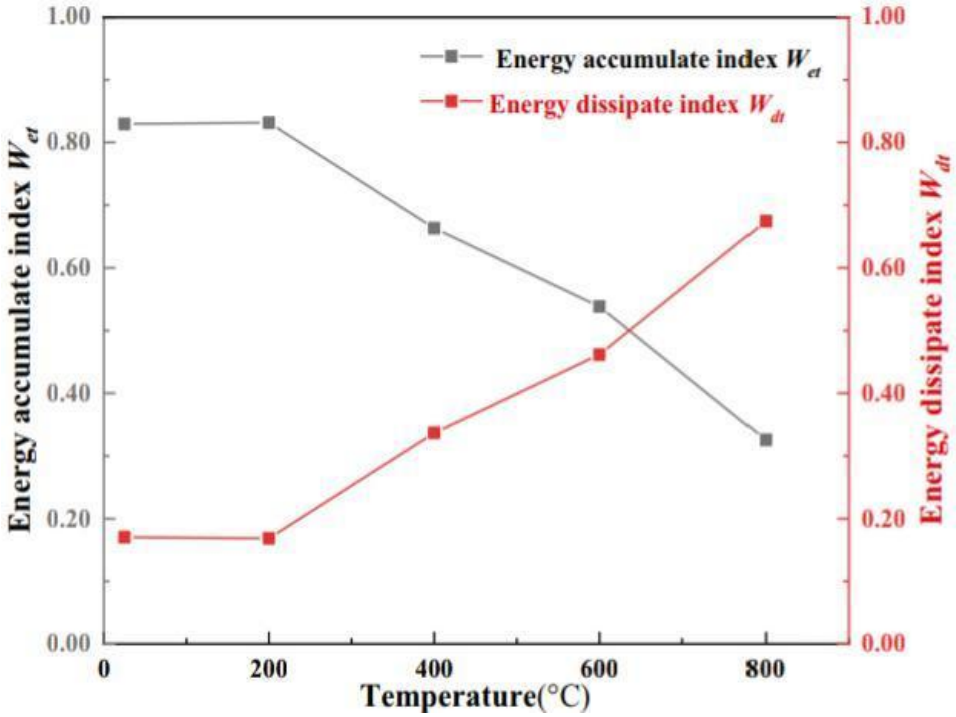



**Figure 2.5** Relationship between energy accumulation and energy dissipation index with temperature as per (Yin et al., 2022)

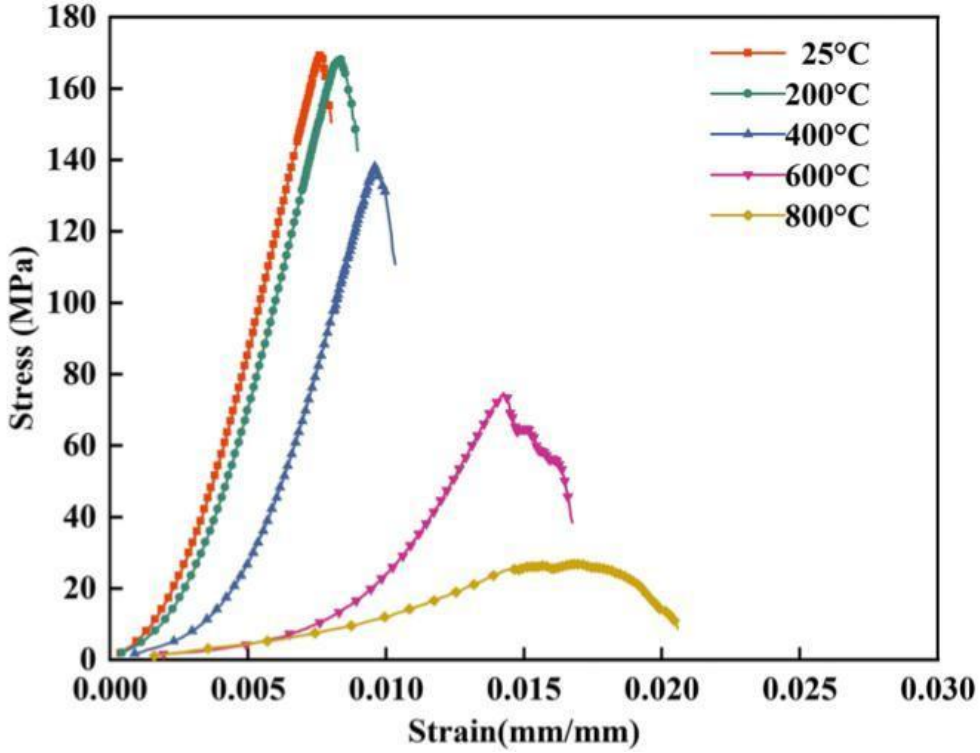



**Figure 2.6** Stress strain curve for granite at different temperature as per (Yin et al., 2022)

Also porosity is said to affect the brittleness of rock, Ye et al. (2022) observed that porosity increases with increasing temperature as shown in figure 2.7. development of pores spaces because of loss of water in void spaces is a key reason. Increase in volume leads to fall in density and Vp as pores spaces increase with temperature this is reflected as n figure 2.8.

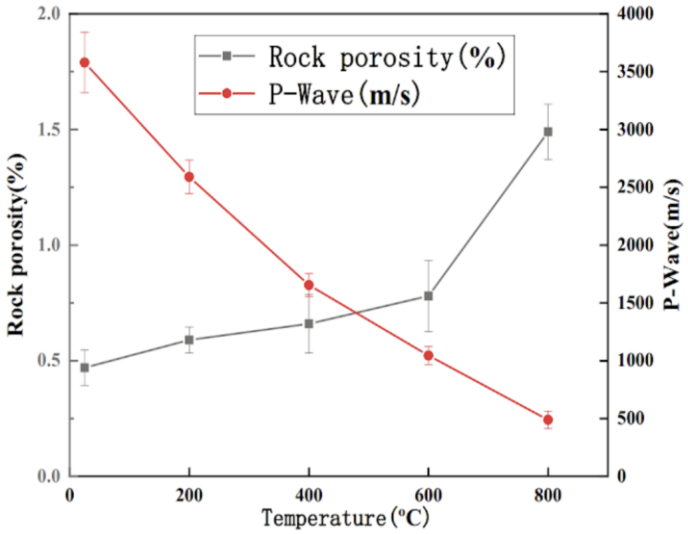



**Figure 2.7** Relationship between porosity and wave velocity with temperature as per (Ye et al., 2022)

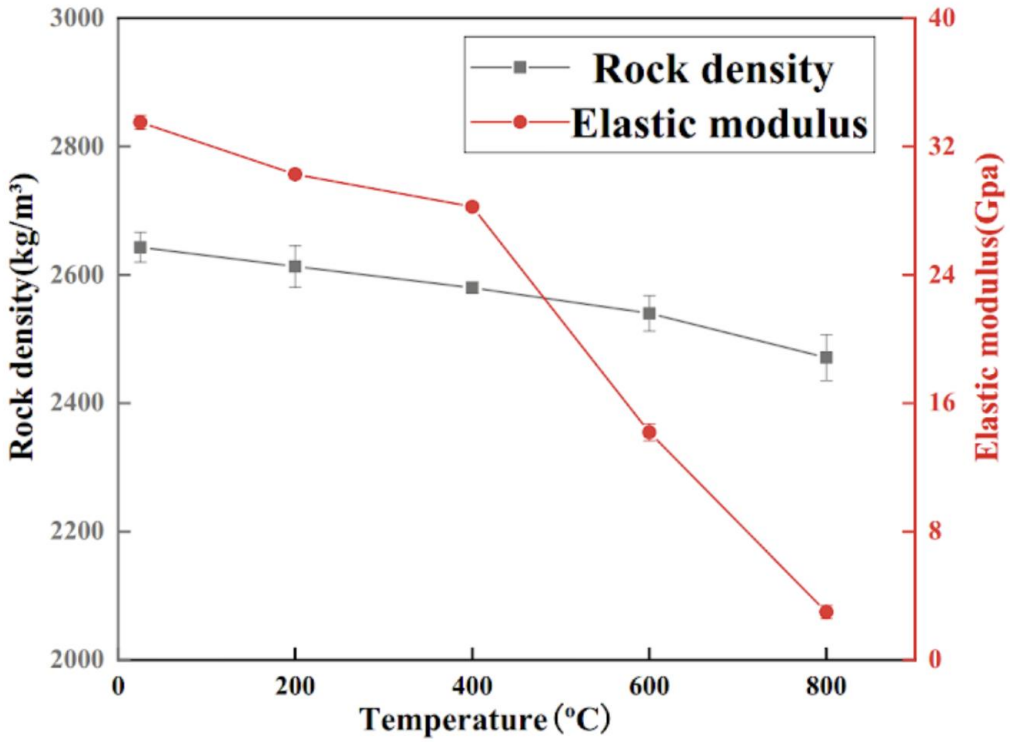



**Figure 2.8** Relationship between rock density and elastic modulus with temperature as per (Ye et al., 2022)

Also elastic modulus was found to decrease with increasing temperature. A higher elastic modulus is an indicator of high strength and brittle rocks are accompanied with high strength.

Energy accumulation index is a measure of accumulated energy within a rock. A brittle rock has the ability to accumulate huge amounts of energy and release the same in a very short span of time, generating phenomena such as rockburst. Energy dissipation index is a measure of energy dissipation ie energy release. Here temperature has a role to play. As per Ye et al. (2022) temperature has the ability to cause energy dissipation, which can be seen from the figure 2.9, initially the energy accumulation index is high indicating presence of excessive energy within the rock, but as the temperature increased the dissipated energy fraction increased, that means energy is getting released and accumulated energy is reducing. Then this thing should have also been getting reflected on rock burst since rock burst are a result of excessive energy accumulation in brittle rocks. The energy is used in generating cracks, ejection of fragments, development of sound etc, all these are characteristic features of rockburst. In simple terms rockburst tendency should decrease with increasing temperature, and that is what actually happens in reality. The tendency of rockburst does decrease with

increasing temperature as per Ye et al. (2022) this is because of increasing energy dissipation index with temperature as shown in figure 2.9 and lowering of energy accumulation index with temperature meaning energy is getting released with increasing temperature.

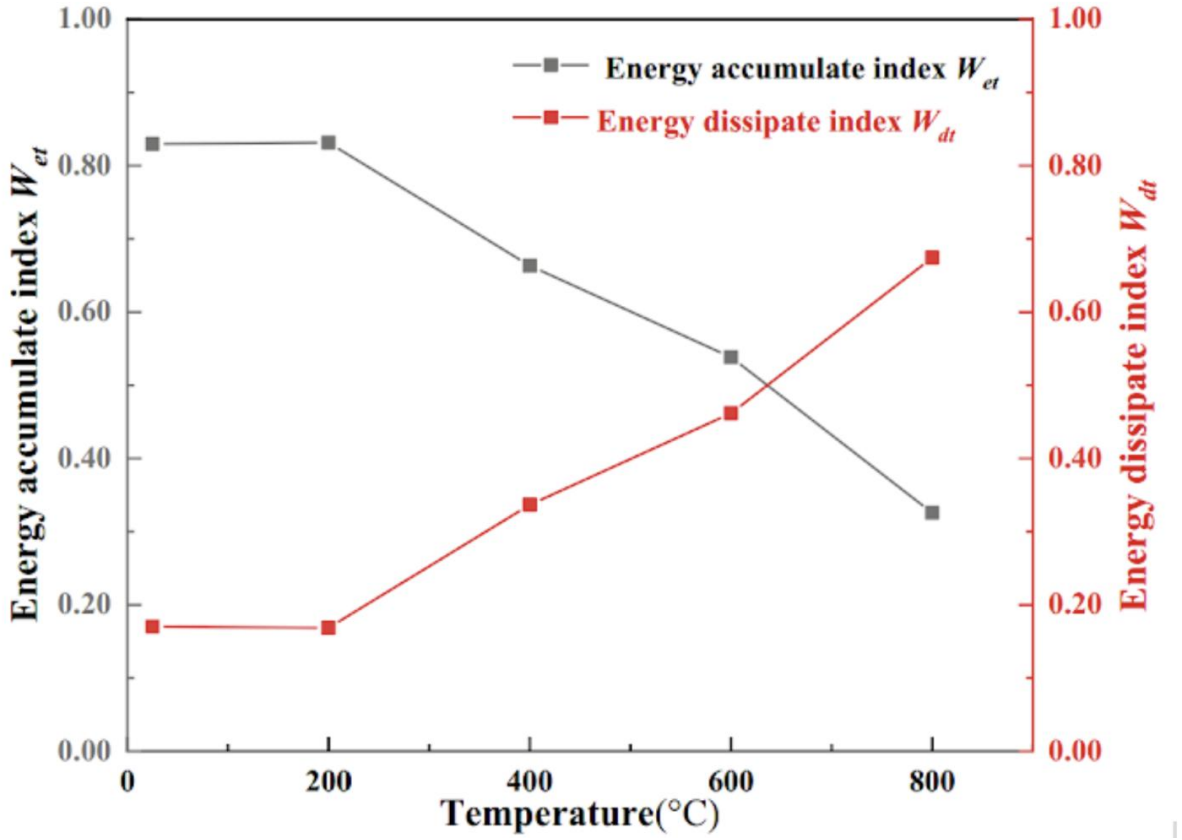



**Figure 2.9** Relationship between energy accumulation and energy dissipation index with temperature as per (Ye et al., 2022)

Temperature even causes changes in size of particles. Based on an experiment conducted by Ye et al. (2022) the proportion of coarse size particles decreased and proportion of ultrafine, fine and medium size particles increased. This means that the energy which the temperature is reducing is getting consumed in internal pulverisation of particles. High temperature somehow is able to cause internal energy dissipation, making particles smaller and smaller and breaking the rock from inside to outside. This thing is reflected by development of cracks on the surface of rock which is granite in case of a study conducted by Ye et al. (2022). This granite has developed cracks on its surface which can be observed by scanning electron microscope image. The density of cracks increases with temperature, the cracks are intergranular and transgranular, meaning between the grains and within the grains respectively. At 25°C intergranular cracks and tensile cracks were present and transgranular cracks were absent but

as the temperature increased transgranular cracks also starts developing and at temperature of around 800°C both these cracks were present.

### 2.4.2 Confining pressure

It was observed that confining pressure has the ability to convert brittle failure of material into ductile failure as the temperature increases. Zhou et al. (2018) stated that angle of internal friction decreases as the confining pressure increases. Zhou et al. (2019) carried out conventional triaxial compressive test along with hydromechanical coupling test and observed that for different confining pressure, acoustic emission event changes for the same loading period, indicating that failure pattern of rock is changing to ductile failure. Ye et al. (2022) also stated that with increasing confining pressure brittle nature of rocks changes into ductile as shown in figure 2.10 actually the stress strain curve of brittle rocks show sudden drop in stress post failure, but under the presence of confining pressure stress strain curve does not reflect that drop post failure, that clearly means that loading conditions do have effect on the brittleness of rock. Hai et al. (2019) Studied the relationship between brittleness and confining pressure of slate, and used stress strain curves for this purpose and came to the conclusion that brittleness decreases with increasing confining pressure. Brittleness behaviour of rock changes into ductile behaviour with increasing confining pressure according to Yin et al. (2022).

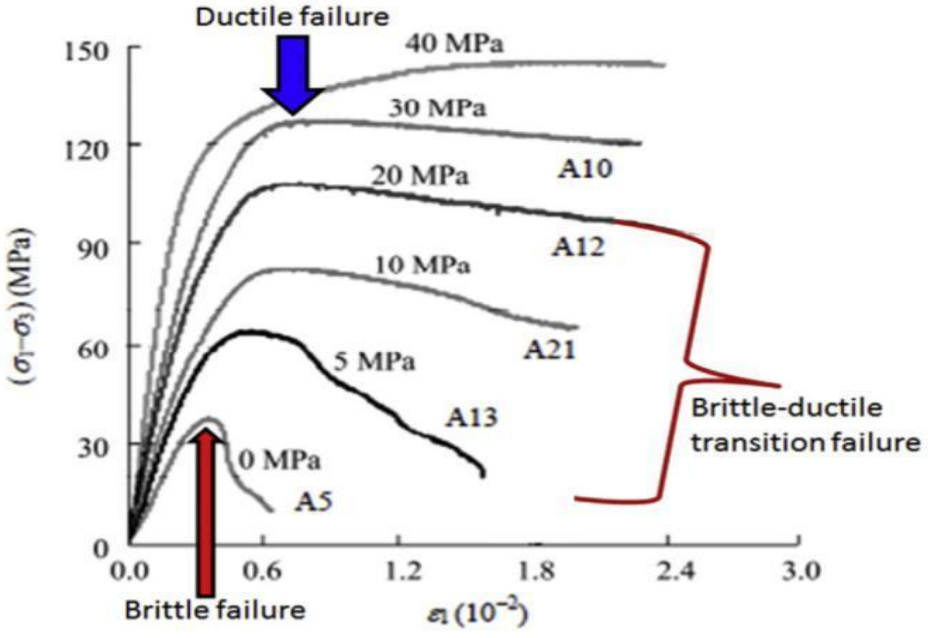



**Figure 2.10** Brittle ductile transition with confining pressure as per (Bai, 2016).

As per Bai (2016) the transition from brittle to ductile is gradual. More Brittle rocks occur in low confinement whereas Ductile rocks occur in high confinement. Sample $A_5$ has higher brittleness than sample $A_{10}$, which was under confining pressure of 30 MPa. as the confining pressure increased from o to 40 MPa, one can observe the flatness in stress strain curve. This gentle transition from brittle to ductile nature of rock is called brittle ductile transition. The reason for this may be that with increasing confining pressure the strength of rock to resist load increases, the ductile failure occurs when load exceeds the strength of rock. But now since the strength of rock has increased because of external confinement, the rock can bear more load as a result brittle nature is not observed in turn generating ductile behaviour in rocks. Higher the confinement of rock flatter would be the stress strain curve and ductile nature would be more predominant.

Relationship between differential stress and confining pressure showing different behaviour of rock as per Bai (2016). The figure 2.11 clearly reflects the different processes happening in rock under different states of stress and confining pressure. For lesser values of confining pressure, brittle nature would dominate and show faulting in the rock because material is undergoing failure. but as the confining pressure is increasing we can observe the general transition in the failure characteristics of rock from brittle to plastic. The semi brittle state represents the transition point in between the brittle and ductile failures in rock. The figure 2.11 represents how the transition from brittle failure to ductile failure occurs with increasing confining pressure. The brittle failure occurs for lower confining pressure, the semi brittle failure for moderate confining pressure and ductile failure at high confining pressure.

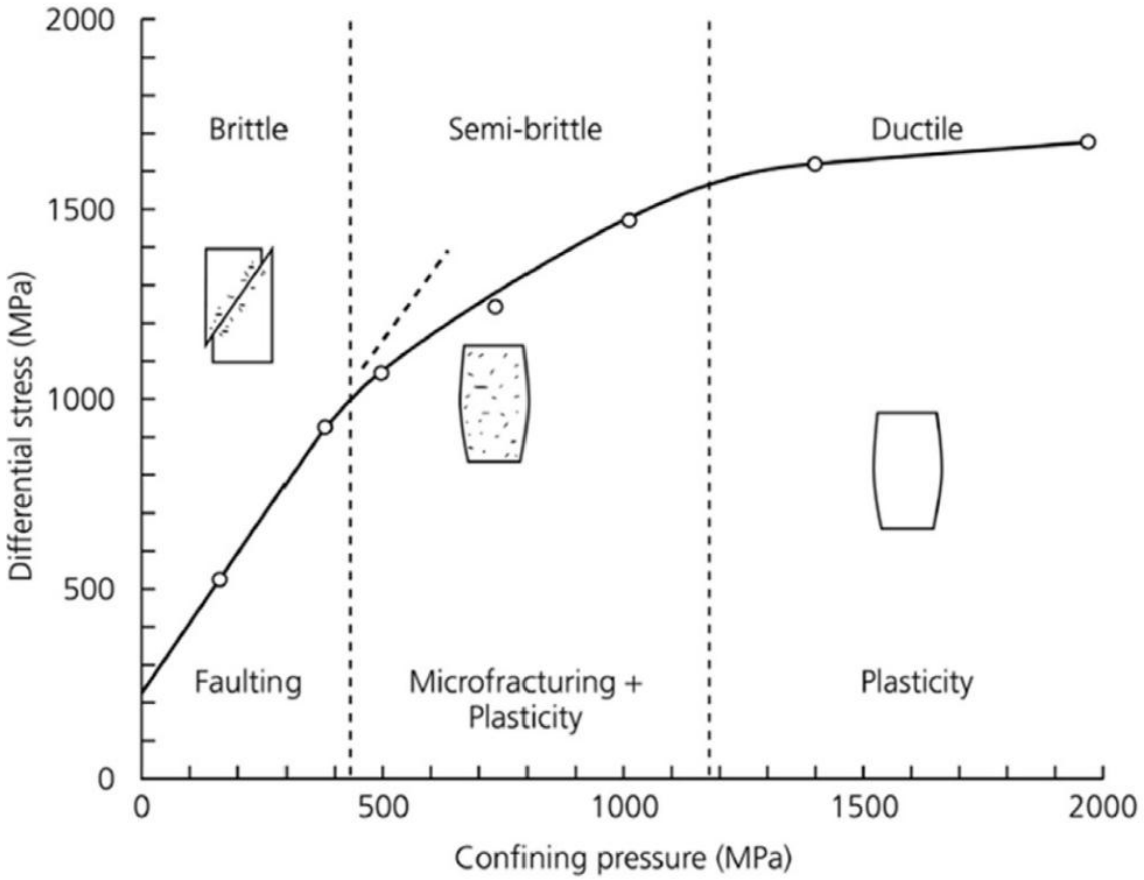



**Figure 2.11** Relationship between differential stress and confining pressure showing different behaviour of rock as per (Bai, 2016)

These stress strain curves will be different for different rocks as shown in figure 2.12 wherein the transition in granite is very sharp as can be seen by stress strain curves indicating highly brittle nature of rock but is milder in case of marble . Initially the post peak stress drop was sharper in marble as compared to sandstone but with increasing confining pressure the brittle ductile transition was more gradual in marble than in granite

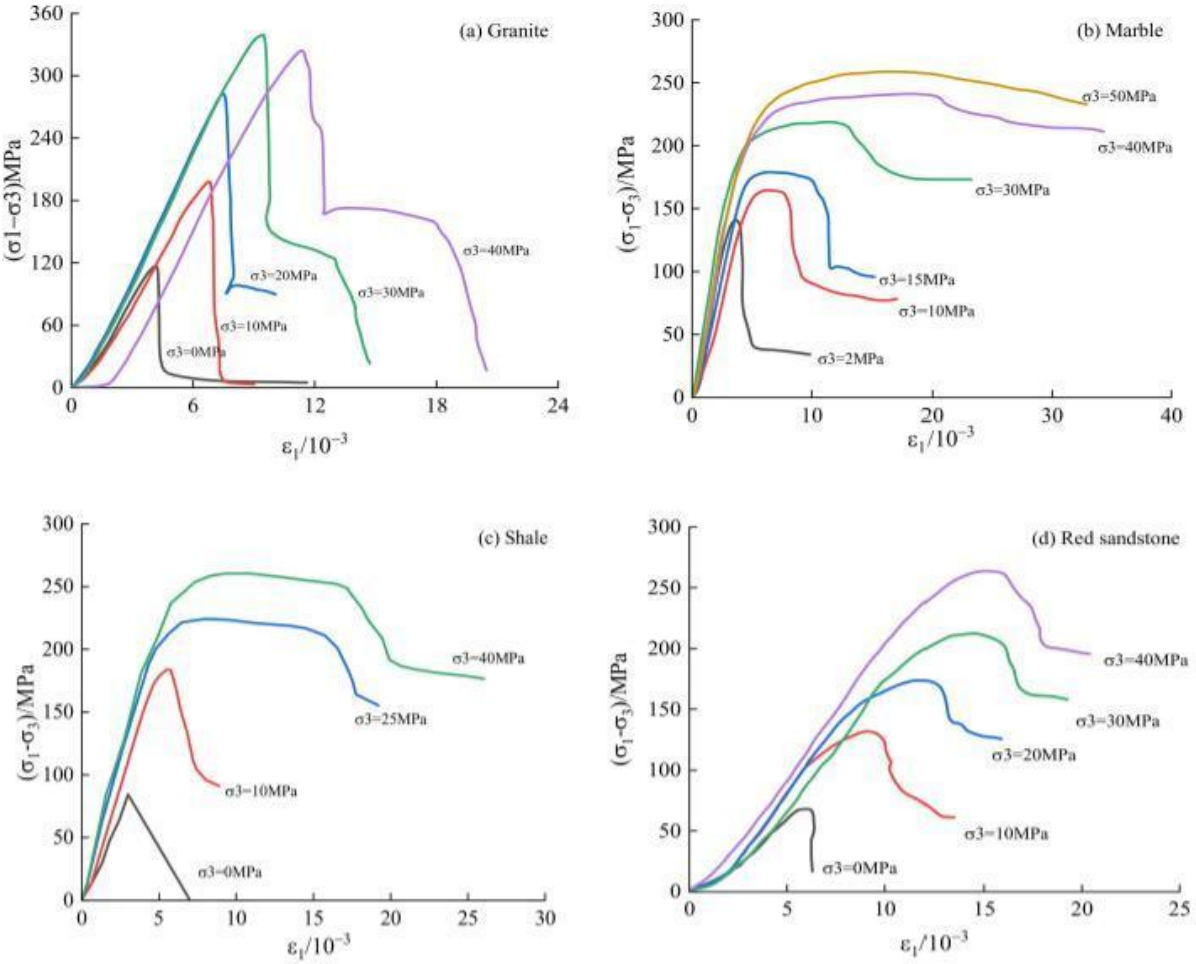



**Figure 2.12** Stress strain curves of different rocks at different confining pressure as per (Xu et al., 2022)

Since brittleness of rock is decreasing then it should be reflected in brittleness indices as well Xu et al. (2022) studied relationship between different brittleness indices and their relationship between confining pressure and observed that what speculated was correct i.e. brittleness indices did decreased with increasing confining pressure as is evident form figure 2.13 and 2.14 . the fall in brittleness index of granite is different than that of other rocks , that might be because granite is a very hard rock it's unconfined compressive strength is higher as compared to other and since these brittleness indices are proportional to strength parameters higher values of brittleness index was observed

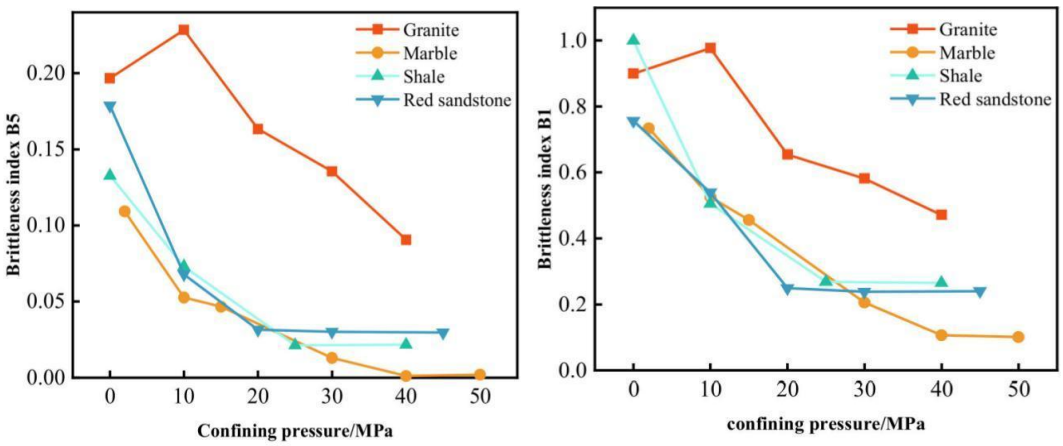



**Figure 2.13 and 2.14** Relationship between brittleness Index $B_5$ and confining pressure and relationship between brittleness index $B_1$ and confining pressure as per (Xu et al., 2002)

### 2.4.3 Strength of rock

Rocks with high strength have more tendency to display brittle failure. These rocks can absorb higher energy as compared to weak rocks. More energy accumulated more will be released and this would generate more extensive cracks. Altindag (2002) studied relationship between brittleness index $B_2$ and Schmidt hammer test readings, their plot is shown in figure 2.15, the Schmidt hammer test which is known as the rebound hammer test, is actually a non-destructive method, meaning that rock is not destroyed during testing, is used to assess the compressive strength of rocks. Herein we measure the "rebound number" (R-value) by striking the rock surface with the hammer, thereafter we use a calibration chart or make use of empirical equation specific to the that rock type so as to convert that rebound number into uniaxial compressive strength (UCS) value. A higher rebound number indicates a stronger rock. Saptono et al. (2013) correlated uniaxial compressive strength with Schmidt hammer rebound values and obtained good correlation between them as shown in figure 2.16. Yagiz (2008) developed a brittleness index based on force penetration tests having force and penetrations as parameters and studied its relationship with uniaxial compressive strength of rocks. The index is obtained by dividing force with penetration. Figure 2.17 and 2.18 shows the relationship between proposed brittleness index and uniaxial compressive strength and Brazilian tensile strength

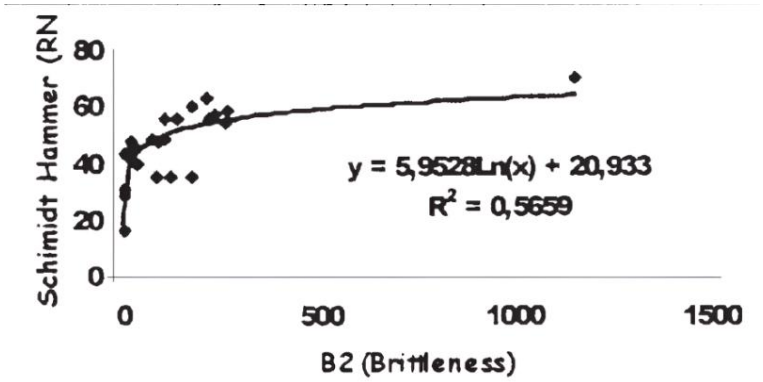



**Figure 2.15** Relationship between Schmidt hammer test and brittleness Index $B_2$ as per (Altindag, 2002)

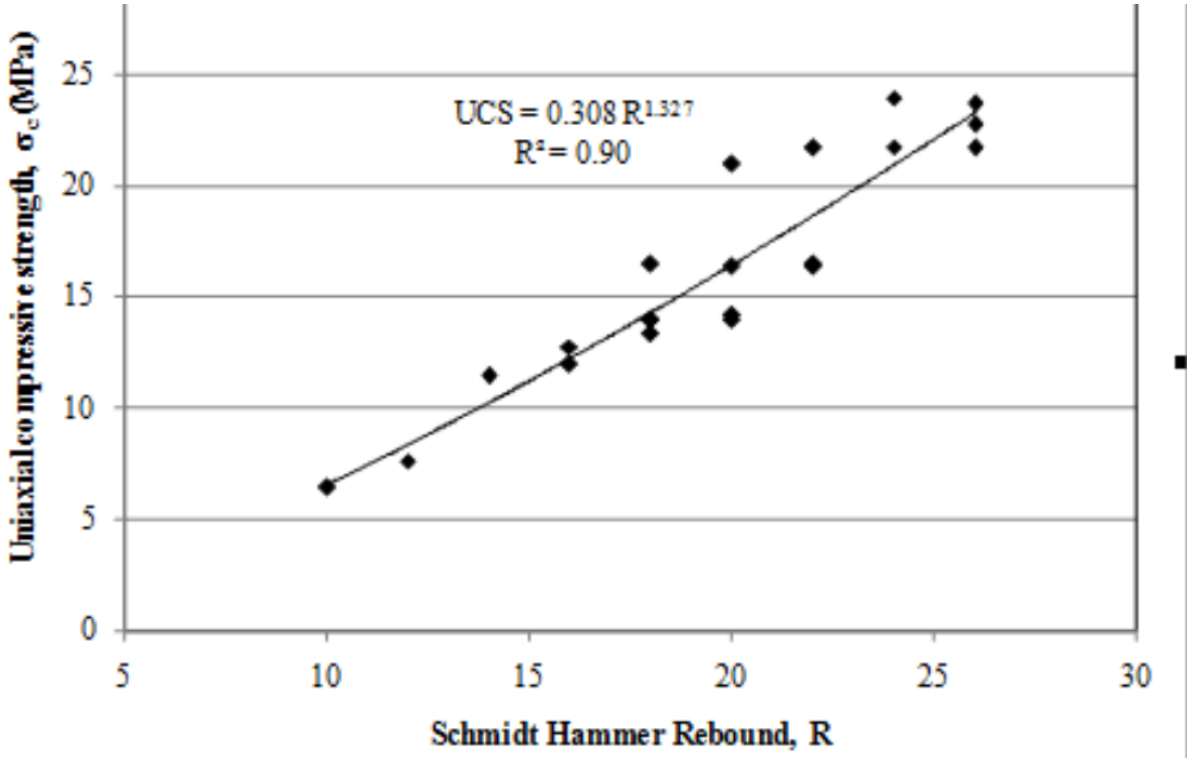



**Figure 2.16** Relationship between uniaxial compressive strength and Schmidt hammer rebound as per (Saptono et al., 2013)

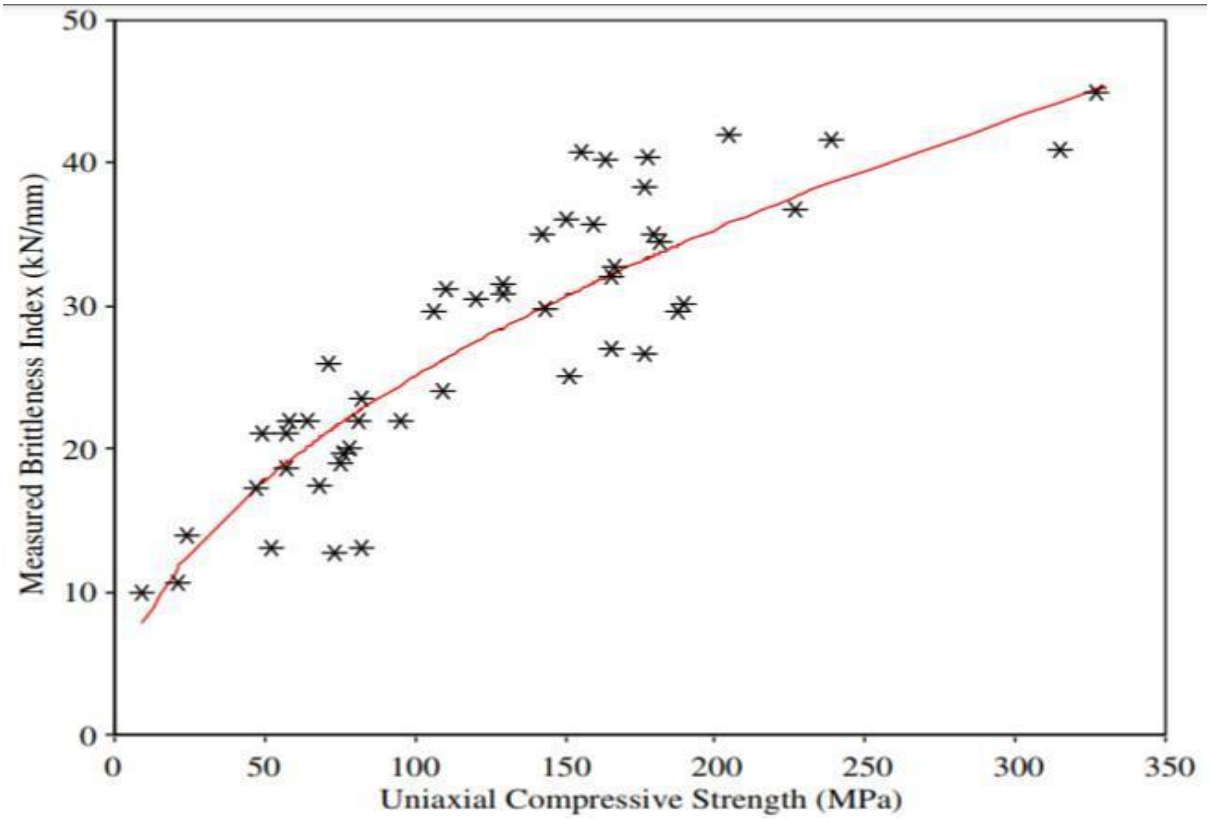



**Figure 2.17** Relationship between brittleness index and uniaxial compressive strength as per (Yagiz, 2008)

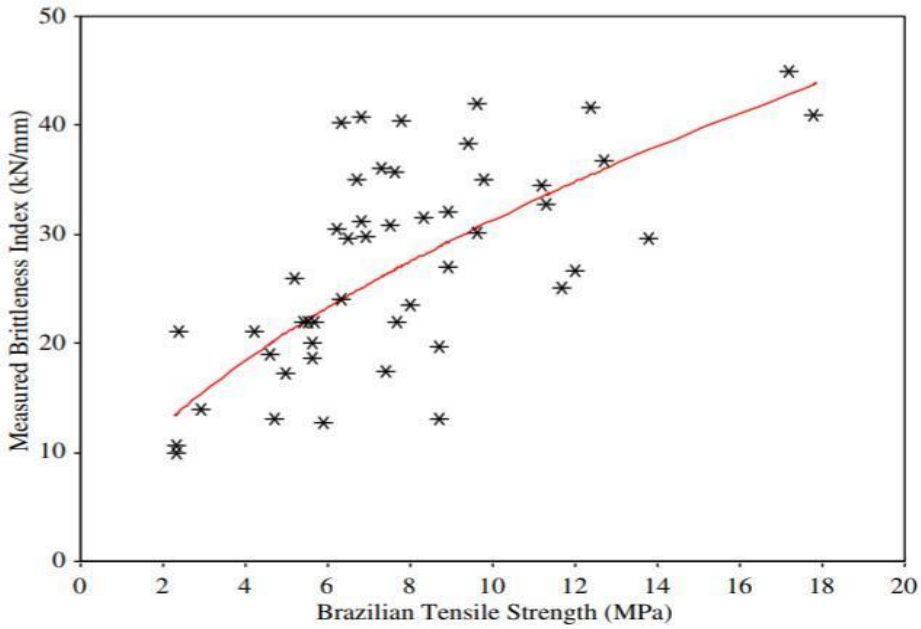



**Figure 2.18** Relationship between Brazilian Tensile strength and the brittleness of the rock as per (Yagiz et al., 2022)

Schmidt hammer test values is an indirect measure of strength of the rock. Higher the values of the test more would be the strength of the rock. These examples represent the fact that the strength of rock is related to the brittleness of rock.

### 2.4.4 Mineralogical composition of rock

The brittleness of rock is related to mineral composition of rock as per Liu et al. (2020). Kang et al. (2020) categorized quartz, feldspar, calcite as brittle minerals and used them in developing brittleness index. The mineral composition of different rocks varies. The presence of different minerals in rocks impart different properties to them .The brittleness of rock is affected by the presence of minerals within the rocks for example minerals like quartz would generate brittle rocks whereas presence of minerals like clay would hinder brittleness of rocks. minerals composition of rocks are obtained by X-Ray diffraction. Presence of minerals with plastic behaviour decreases porosity as per Heidari et al. (2014).rocks having minerals like quartz and feldspar experiences sudden drop in stress post failure whereas the ones having minerals like clay and carbonate do not experience sudden drop in stress according to Liu et al. ( 2020). Certain minerals were found to have direct influence on properties of rock like for example clay content of rock was found to have positive correlation with the Poisson's ratios whereas quartz was inversely related to the same as per Wu et al. (2024). The rock properties are more sensitive to brittle minerals like quartz than to minerals like clay, as per Liu et al. (2020). Minerals like carbonate had a positive relationship with Poisson's ratio whereas quartz had a negative relation according to Liu et al. (2020).Ye et al. (2020) developed a brittleness index considering the mineral content of the rock, herein minerals like quartz, feldspar, calcite were considered as brittle minerals generating a brittle rock whereas clay was considered as plastic mineral. Also it was found that the brittleness of rock increased with increasing quartz content. Sun et al. (2021) discussed the importance of rock brittleness in shale gas extraction, brittle minerals have a role in shale gas migration. occurrence of brittle minerals were related to presence of pores in shale rocks as per Sun et al. (2021). The presence of brittle minerals like quartz produces ideal conditions for generating artificial fractures to enhance permeability of strata. Because these fractures won't close slowly with time, unlike ductile fractures which close earlier. So a reservoir having a higher proportion of brittle minerals would be favourable for shale gas extraction. Ye et al. (2020) states that there is no common consensus on categorization of minerals as brittle or ductile, apart from minerals like quartz it is controversial whether minerals like carbonate, pyrite, and feldspar are brittle minerals or not.

Lie et al. (2023) studied the effect of mineral content on the mechanical properties of rock; shale rock was considered for the same, the rock was obtained from longmaxi formation, sichuan basin in China. The mineral composition of the rock was clay and quartz with 34.6% and 40.5% content respectively and other minerals like potash feldspar and plagioclase. A triaxial test was conducted on these samples and other parameters like UCS were derived. Similarly X-ray diffraction technique was used to compute the mineralogical composition of shale. The data obtained was plotted. From the fig 2.19 it can be clearly observed that the presence of brittle minerals in rock improves the mechanical properties of rock , since brittleness indices are also based upon them the brittleness indices indicate high value. minerals like silicate have high strength and those like clay have low strength, and the rocks made up of these minerals will reflect the same. Now since it's the characteristics of brittle material to absorb huge amounts of energy and then release the same in a short span of time, the mineral should have strength, cause otherwise without this the rock won't be able to accumulate that energy. That's why minerals like quartz are brittle as reflected by the fig and minerals like clay are not. Compressive strength and Young's modulus increases with brittle mineral content and Poisson's ratio decreases with the same, the opposite is true for ductile material dominated by minerals like clay.

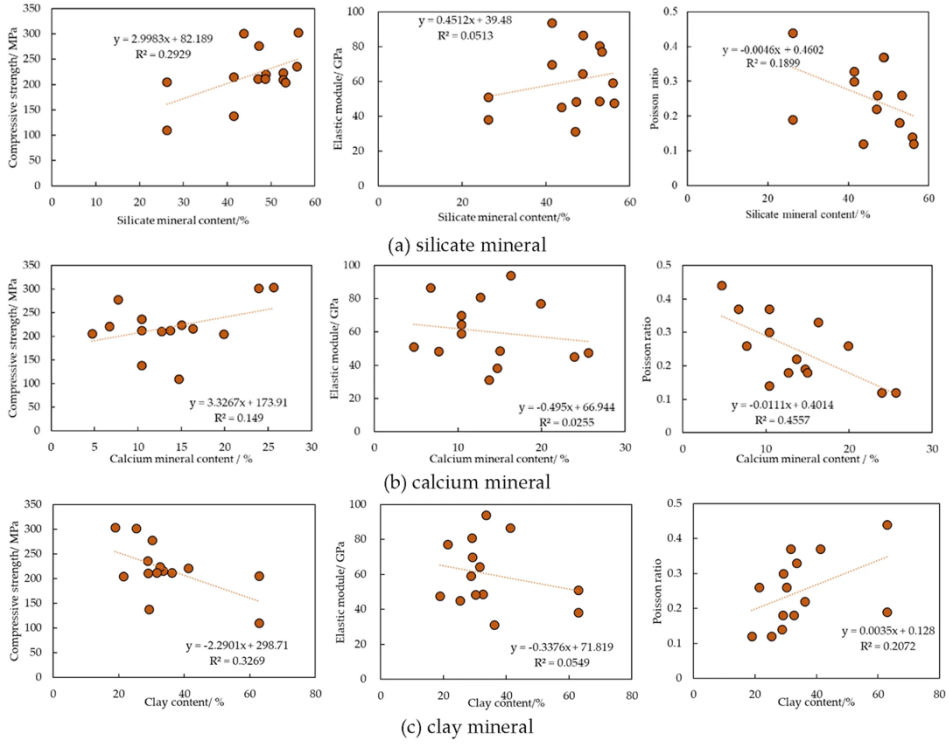



**Figure 2.19** Effect of mineral content of rock on different mechanical properties as per (Lie et al., 2023)

### 2.4.5 Shape and size of minerals grain

The shape and size of minerals grains have a profound influence on the stress distribution within rocks. Specific arrangements of grains can cause stress concentration, whereas other ones may not. Wu et al. (2024) stated that brittleness of rock was affected by diameter of mineral grain as well as the degree of cementation of the rock. Yilmaz et al. (2009) stated that when the relative proportion of different brittle minerals in rocks are the same, then grain size plays a dominant role in determining the brittleness of rock. Grains which have higher size than others will definitely have larger grain boundaries as well as according to Yilmaz et al. (2009) and these boundaries have a role to play in the development of cracks. Hajiabdolmajid and Kaiser (2003) stated that finer grained rock is less brittle than coarse grained rock. Eberhardt et al. (1999) observed that fracture creation and propagation was much easier in coarse grained rock than in fine grained rock; Actually the coarse grained rock would have higher crack length and as a result according to griffith law lesser stress would be required for crack propagation.

Gunes et al. (2009) made use of point load test and size of grains to compute brittleness of different granite samples and states that the brittleness of granite with the largest grain size was more than twice that of other two kinds of granite with identical mineral composition. Zhang et al. (2016) commented that larger grain size will make the rock easier to fracture.

### 2.4.6) Porosity

Porosity can be defined as the ratio of volume of void to total volume of rock. Porous rocks are the ones which have pores within them wherein air or water remains trapped. These pores may be interconnected or isolated with respect to one another. Interconnected pores impart permeability to the rocks wherein these interconnected pores provide passage for flow of water. Porosity has an adverse effect on the strength of rock.

According to Wang et al. (2023) porosity does have an impact on the brittleness of the rock along with deformation, strength and permeability evolution. More porous the rock less would be its strength as per Zhang et al. (2017). Xie et al. (2010) expressed that some scholars believed in the relationship between porosity and brittleness of rocks. As per Heidari et al. (2014) brittle rocks and softer rocks differ in the strain they develop at failure, those are namely low strain and high strain respectively, therefore it can be concluded that with rise in porosity; strains will increase and brittleness will decrease. Howarth et al. (1987) stated that porosity has an

influence on the drillability of rock because high porosity will favour crack formation within the rock. Chen et al. (2014) stated that higher porosity along with organic content would favour shale gas extraction and hence the production. Zhang et al. (2017) stated that lower porosity corresponds to higher brittleness values also porosity along with mineralogical composition plays an important role in hydraulic fracturing. Ye et al. (2020) stated that porosity increases when brittleness decreases.

When the relationship between porosity and brittleness was studied by Heidari et al. (2014) It was observed that porosity and brittleness were poorly correlated with one another. The brittleness indices $B_1$, $B_2$ and $B_3$ were considered in this study. The porosity test was carried out on rocks in an air dried and saturated state, one of them is shown in figure 2.20 .The rocks which were considered for study were gypsum, sandstone, travertine, marble, Monzogranite, tuff, hornfels, and holo leucogranite

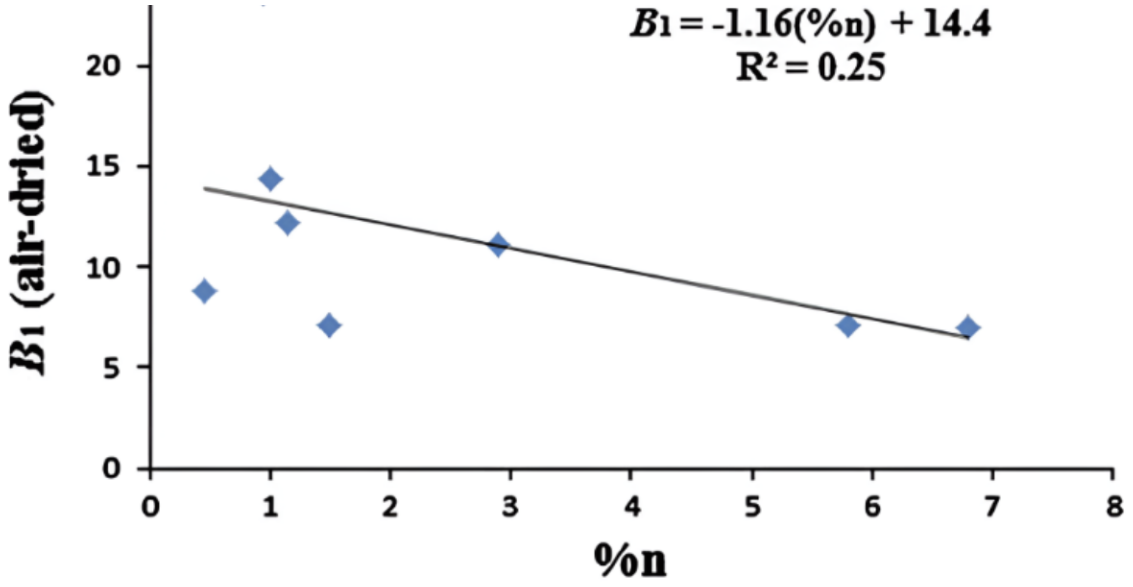



**Figure 2.20** Relationship between brittleness indices and porosity of different rocks as per (Heidari et al., 2014)

### 2.4.7 Texture

Texture of rock to the shape size and orientation of grains within the rock. According to Ye et al. (2020) rock texture is primarily responsible for brittleness characteristics of rock like the laminar structure of shales and the fine-grained micritic textures of carbonate rocks.

### 2.4.8 Total organic content(TOC)

Total Organic content refers to carbon compounds, generated from dead remains of plants and animals. The amount and maturity of shale negatively affects the brittleness of rock as per Wood and Hazra (2017) because organic content acts as a glue in between the particles and absorbs stress.Hu et al. (2015) Stated that with Young's Modulus decreases with increasing organic carbon content. Higher Young's Modulus means that rock is brittle in nature, the opposite of which means ductile. Higher content of TOC signifies a ductile rock as per Verma et al. (2016). This is useful in identification of sweet spots in case of Shale gas extraction.

### 2.4.9 Bedding angle

The bedding angle can be defined as the angle in between the bedding plane and a reference direction. For example while computing the uniaxial compressive strength the reference direction would be that of applied load. Hao et al. (2019) studied the effect of bedding angle on geomaterials and found that the brittleness of material first increased with bedding angle reaching maximum values at 45° and thereafter decreased. Figure 2.21 shows the relationship between bedding angel and brittleness index.

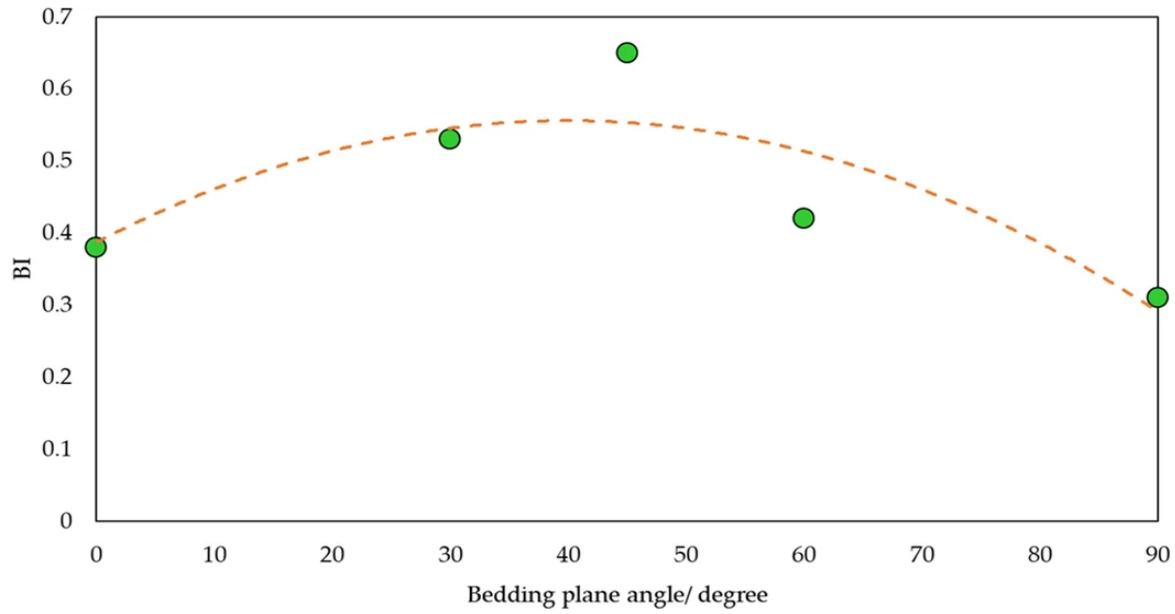
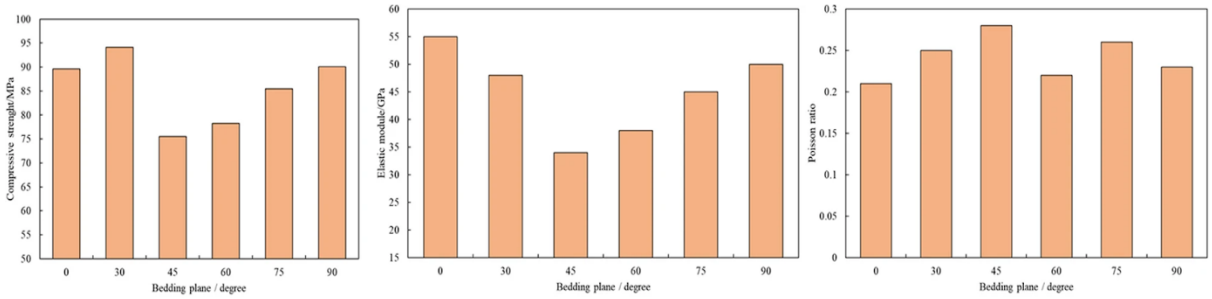



**Figure 2.21** Relationship between bedding plane and brittleness of Shale as per (Lie et al., 2023)

Lie et al. (2023) states that the higher value of brittleness index at 45° was because of the failure model of shale . Basically these bedding planes are a plane of weakness in rock such that upon application of load the rock would try to break along these planes. The breakage of rock along these planes will be fast as a result it will display brittle failure. However, if we study the plot as shown in the figure 2.22 the mechanical properties are minimum at the respective angle and Poisson's ratio is high indicating a ductile material, therefore the value of index at 45° should be the minimum one and not maximum.




(a)compressive strength (b)elastic module (c)Poisson ratio

**Figure 2.22** Mechanical properties of shale at different bedding angles as per ( Lie et al., 2023)

### 2.4.10 Weathering of rock

Brittleness decreases with increase in weathering of granite as per Gong and Zhou (2007) because weathering affects the internal structure of granite and its strength cohesion and strain energy storage capacity decrease.

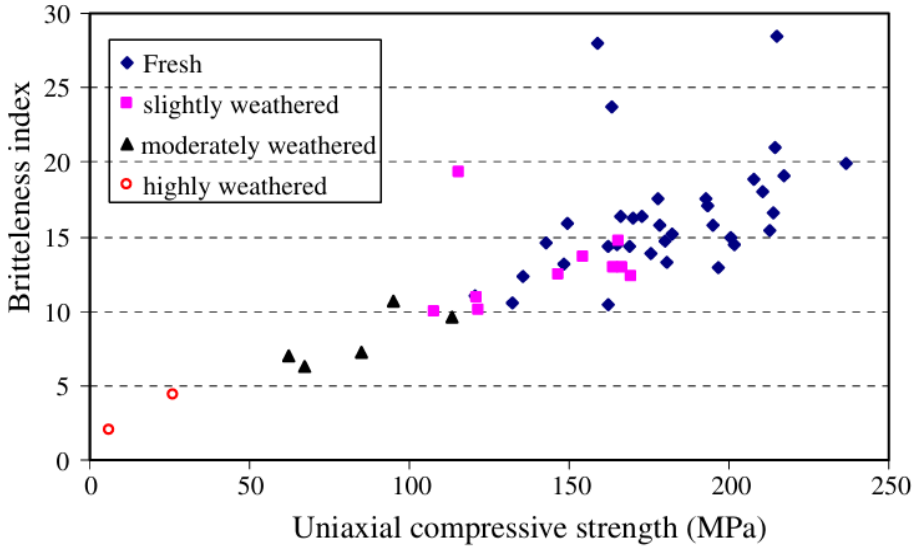



**Figure 2.23** Influence of weathering on the brittleness Index as per (Gong and Zhao, 2007)

From the fig 2.23 it can be observed that the strength of rock which was granite in this particular study was found to decrease, and the brittleness index used for this study was $B_2$.

The granite samples were taken from the tunnel face of kranji Tunnel, thereafter unconfined compressive strength tests and Brazilian tensile strength tests were carried out on those samples. The UCS of fresh granite was in the range of 160-250 MPa whereas that of highly weather one was less than 50MPa. The brittleness index value of fresh granite was in the range of 10-28 whereas that of highly weathered granite was lesser than 5.

### 2.4.11 Undrained or drained test conditions

Holt et al. (2015) discussed the effect of drained or undrained state of rock sample on the brittle behaviour, the plot generated is shown in figure 2.24. Consolidated undrained triaxial tests were conducted on the shale rock which were saturated with water. The resulting stress strain curve clearly shows that the drained shale sample clearly depicted more brittle behaviour as compared to the undrained sample. similar observation was shared by Tirayaki (2006) wherein it was stated that wet rocks tends to behave in ductile manner whereas absence of water makes the rock behave in brittle manner

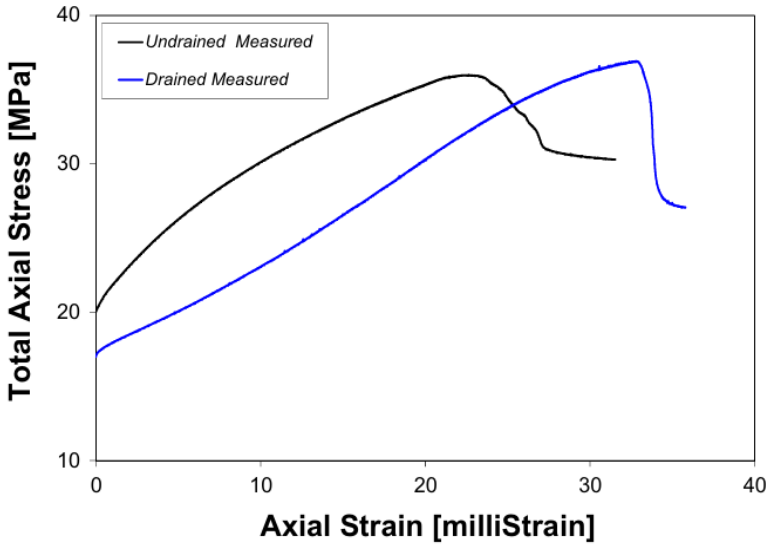



**Figure 2.24** Stress strain curve for drained and undrained state as per (Holt et al., 2015)

### 2.4.12 Depth of rock

A large number of rock mechanics studies have shown that with the increase of the buried depth, the rock property will gradually change from brittleness to plasticity, which is related to the geostress, temperature, formation of water, etc as per Ye et al. (2018). The cost of shale gas extraction increases with increasing depth of shale as per Silva et al. (2015). however when Lie et al. (2023) studied the effect of depth on brittleness of shale it was observed that brittleness index value at depth of 4000m was 0.56 whereas the same at depth of 4100m was 0.33

Some other factors are as follows

- Material anisotropy as per Holt et al. (2015)
- Texture as per Ye et al. (2022)
- State of stress as per Liu et al. (2024)
- Lower strain rate favours ductile deformation of rock as per Tirayaki (2006)

## 2.5 Role of brittleness in excavation of rock

Excavation in rock is carried out for a variety of purposes ranging from mining of minerals, construction of tunnels, preparing foundation of building, creation of trenches, debris removal, dredging etc , covering different industries and vast variety of applications. Excavation can be carried out by either drill or blast techniques or by using mechanical excavators. The main aim of these methods is to break the rock and remove it from its place. Drilling is an integral part of major excavation operations, which involves rock tool interaction. If this part is not properly understood then, Drilling cost can increase apart from that loss of equipment, delay in project, drill bit wear, rise in noise levels can occur. Rock with higher values of brittleness develop more crack formations and chipping according to Gong and Zhao (2007). Also the brittleness of rock was used for predicting the performance of tunnel boring machines through the NTNU model as per Bruland (1998). There are many parameters of rock which are taken into consideration during excavation like hardness, toughness, strength etc however, pertaining to the topic we shall focus on brittleness of rock.

### 2.5.1 Specific energy

It is the energy required to cut and produce a unit volume of rock. Tirayaki (2006) stated that as the tensile strength of rock increases the specific energy increases as well; the specific energy decreases with increasing porosity of rock. Specific energy simply tells us how much energy is consumed to break unit volume of rock as per Dursum and Gokay (2015). Singh (1987) stated that specific energy was directly proportional to the brittleness of rock. Balci et al. (2004) stated that specific energy can be used for measuring the performance of excavation equipments.As per the fig 2.25 shown below rocks having higher strength are bound to consume more energy as they ought to offer more resistance to penetration by drill bit. Initially the specific energy is high but as the penetration rate increases the specific energy decreases.

Goktan and Yilmaz (2005) do not find any meaningful correlation between brittleness and specific energy

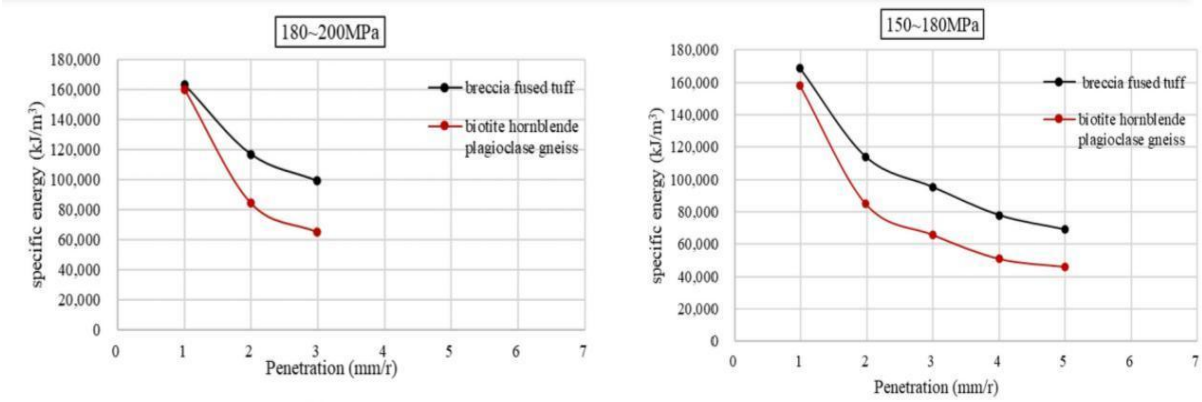



**Figure 2.25** Relationship between penetration rate and specific energy for rocks with different uniaxial compressive strength as per (Dursun and Gokay, 2015).

Balci et al. (2004) carried out a study to understand the relationship between specific energy and other mechanical properties of rock. Certain tests including uniaxial compressive strength test, Schmidt hammer test were conducted on the rock samples, thereafter statistical methods were used to obtain the required correlations. Good correlations were obtained in between the specific energy and uniaxial compressive strength and tensile strength.

Specific energy is important from the point of view of comparing efficiency of different machines used in excavation. Like one which has less specific energy would be more efficient than other and specific energy is inversely proportional to cutting efficiency. Singh (1987) reported correlation between cuttability, penetrability and Protodyakonov strength index of coal with brittleness. Altindag (1983) also mentioned that specific energy does have a correlation with brittleness. Singh (1986) tried to correlate in seam coal cutting performance with the brittleness index which was based on the compressive and tensile strength of the rock.

Altindag (2003) tried to correlate specific energy along with the brittleness index which was based on the tensile strength and compressive strength of the rock.

Dursun and Gokay (2015) studied the relationship between specific energy and brittleness of rock, wherein simple and multiple regression analysis was performed on the data obtained by performing various tests like Brazilian tensile strength onto 24 different rock samples. brittleness indices $B_1$, $B_2$, $B_3$ ( based on strength parameters) and $B_9$ based on percentage of fines were computed.

Li et al. (2024) studied the influence of rock brittleness on tunnel boring machine's performance and found that as the UCS of the rock increases it offers more and more resistance to penetration by cutting bits, this is reflected by figure 2.26. Specific energy is a parameter which reflects this particular behaviour of rock, a rise in specific energy means more energy is required to break the rock. From Fig 2.26 it can be observed that for different ranges of UCS how different rocks behave. Specific energy was found to be related with different parameters such as depth of cut, pick type, pick geometry, line spacing, etc as per Dursun and Gokay (2015).

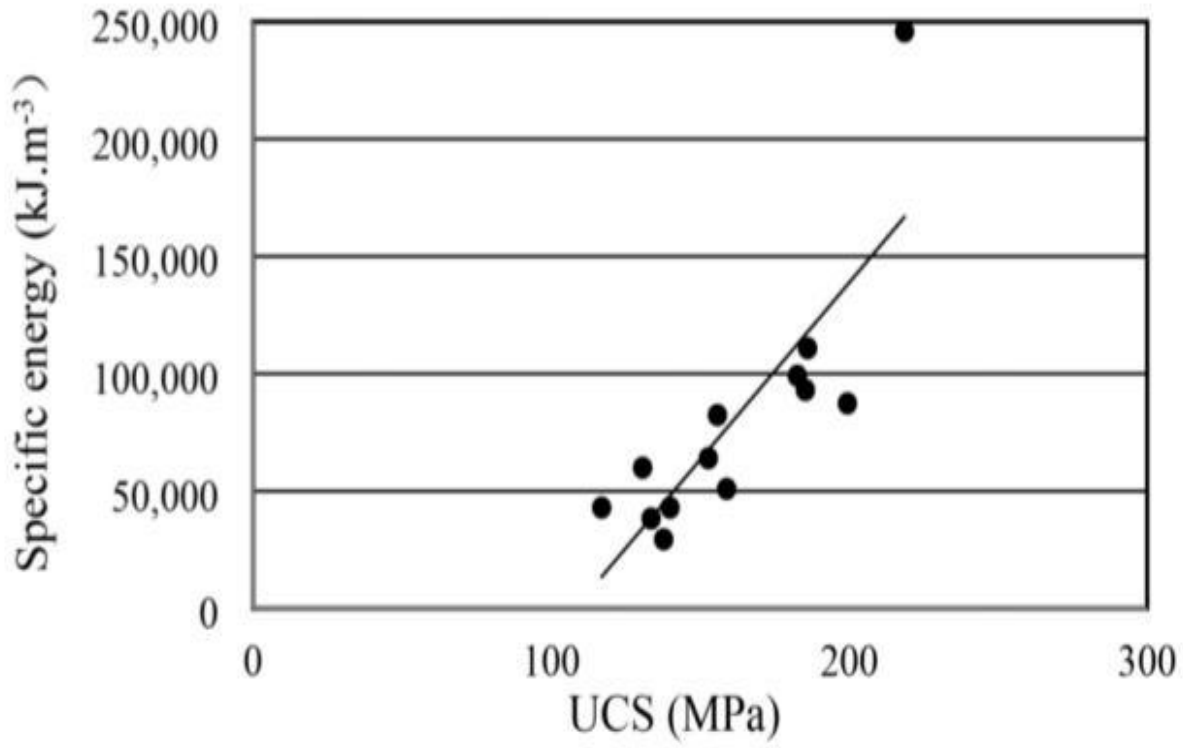



**Figure 2.26** Relationship between specific energy and UCS of rock as per ( Li et al., 2024)

Dursun and Gokay (2015) developed equations for predicting specific energy based on cutting tests, there were two equations one for predicting mechanical specific energy and other one electrical specific energy. The different parameters under consideration were average cutting force acting on the tool (FC) , cutting length in cm (L), Average net power in KW (P), cutting time (h) , volume of rock cut as Q. While test was conducted the test parameters were as follows cutting depth was 2 mm cutting speed was 36 cm/s, rake angle was -5 ° , clearance angle was 5° ,Pick tip was made of tungsten carbide (10 % cobalt) , pick width was 12.7 mm and data sampling rate was 1000 Hz. They are shown in figure 2.27 .

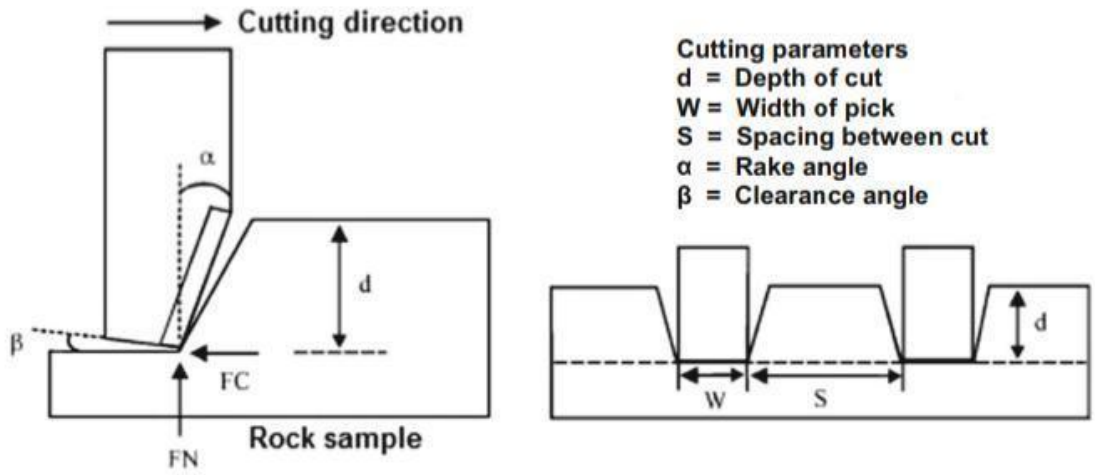



**Figure 2.27** Rock cutting parameters as per (Dursun and Gokay, 2015)

The rock cutting test is performed on two manner, one relieved and other unrelieved , herein the depth of cutting and line spacing affects the specific energy as If the line spacing between grooves is small, rock in between the groove would be over crushed whereas if it's too large cutting would not happen properly. In both these cases specific energy of rock would be high. In case of unrelieved cutting mode spacing is large and so would be specific energy as well. There were two sets of data considered for determining specific energy categorized on the basis of relieved or unrelieved depth.

Balci et al. (2004) Carried out the laboratory testing programme includes full-scale rock cutting and physical and mechanical property tests on samples and thereafter applied statistical methods onto the data obtained to generate correlations between parameters.

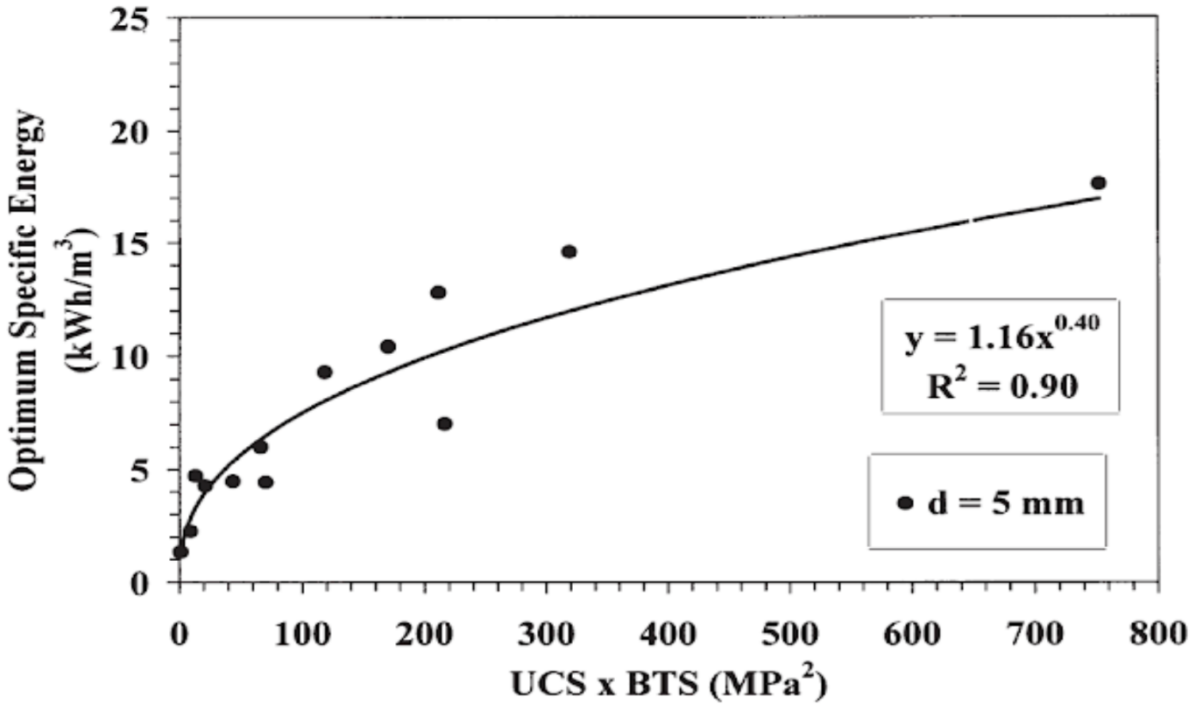



**Figure 2.28** Relationship between specific energy and product of uniaxial compressive and tensile strength test as per (Balci et al., 2004)

From the fig 2.28 we can observe how the specific energy is increasing with increasing compressive and tensile strength of the rock. We also have a brittleness index based on the product of uniaxial compressive strength and tensile strength. This shows that as the brittleness of rock increases the specific energy also increases. The value of d represents the ratio of optimum cut spacing and cut depth.

Comakli et al. (2016) studied correlations between specific energy and brittleness indices and obtained good correlations between specific energy and brittleness index $B_5$ ,as per the figure 2.29 as the brittleness of rock is increasing so does the specific energy. Meng et al. (2020) also confirmed that higher proportion of energy is required to generate fracture in rocks with high brittleness and more crack formation occurs in that case whereas in case of ductile rocks less cracks formation occurs and energy gets consumed in larger inelastic deformation.

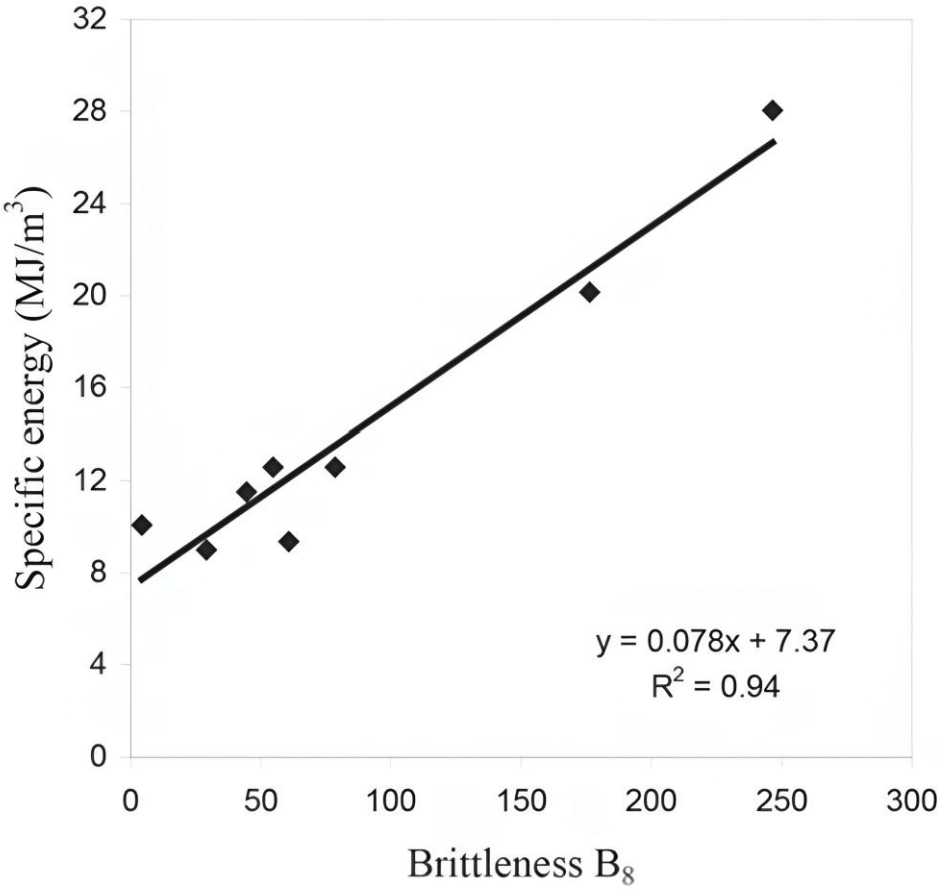



**Figure 2.29** Relationship between specific energy and brittleness Index $B_8$ as per (Comakli et al., 2016)

## 2.5.2 Drillability

It can be defined as ease of drilling through rock and it is a combined function of various properties of rock like mineral composition, grain size etc. It basically tells us how easy it is to drill through a rock. Yarali and Kahraman (2011) defined drillability as the rate of penetration of a drill bit into the rock. It depends on several factors like mineralogical composition of rock, its grain size , weathering of rocks etc.

Yarali and Kahraman (2010) classified parameters affecting drillability of rocks into two categories namely controllable and uncontrollable, the type of bit, flushing , thrust applied was placed under controllable parameters whereas rock properties and geological conditions were placed in category of uncontrollable parameters. Tang et al. (2016) stated that drillability of rock is affected by brittleness of rock as well as the fracability.

Yarali and Soyer (2011) laid down various parameters affecting the brittleness of rocks as shown in figure 2.30 rock mass factors are the ones which we cannot control, like the type of

rock, namely whether it's igneous, metamorphic or sedimentary. we know that igneous rock have high strength and as result they would offer higher resistance to drilling as compared to others, this high resistance would reflect itself in form of high bit wear, lesser penetration rate, higher cost of drilling, more time consumption , more noise generation etc. rock mass jointing is another factor, if the rock is jointed then are we drilling in direction of dipping beds or opposite of them that becomes important as well, also jointed rocks can cause wedge failures in underground excavations presenting threat to safety of workers.

Other factors were the type of rocks and their continuity, frequency and orientation. machine factors such as type of bits, there are a variety of bits like drag bits, tricone roller bits etc used in different types of drilling like whether it's rotary , percussion lor rotary percussion drilling. rotation means how fast the bit is rotating ,it's expressed in rpm. The operating process includes which method of drilling is carried out, experience of the operator, logistics support etc all these are man based parameters relying on experience. The last ones are geological parameters focussing on the physical and mechanical properties of rocks like strength parameters , hardness , toughness, textural parameters like shape and size of grains and apart from them are the empirical parameters including the specific energy and various drillability indices.

Evans and Pomeroy (1966) stated that impact energy developed by cutter pick was inversely proportional to the brittleness of rock. Fish (1968) stated that penetration rate of rotary drills was found to be directly proportional to applied thrust and was inversely proportional to the uniaxial compressive strength of rock. Selmer-Olsen and Blindheim (1970) stated that brittleness was one of the key factors affecting rate of penetration inside the rock. Selim and Bruce (1970) made use of quartz content which is itself a measure of brittleness of rock, in computing the rate of penetration inside the rock. Pathinkar and Misra (1980) obtained a good correlation between the penetration rate inside the rock and specific energy.

| Rock mass factor (Lislerud, 1988) | Machine factor | Operating process (Thuro and Spaun, 1996) |
|---|---|---|
| Rock type | Drilling machine type | Drilling methods |
| Rock mass jointing | Thrust force | Operation and maintenance of machine rig |
| Type and continuity | Bit type | Experience of operator |
| Frequency | Rotation | Logistic support |
| Orientation | The quality and intensity of flushing | |
| Hydrothermal decomposition | Power transfer | |
| Stress distribution in rock | | |

| Geological parameter (Chen and Vogler, 1992; Thuro and Spaun, 1996) |
|---|
| Strength properties, such as uniaxial compressive strength, tensile strength, point load strength. |
| Hardness, such as Schmidt rebound hardness, total hardness, Mohr hardness, Shore scleroscope hardness, NCB cone indenter |
| Energy properties, such as fracture toughness, toughness index, critical energy release rate and acoustic emission properties. |
| Rock internal texture, such as grain size, grain shape, mineral composition, porosity, cementation and cementation degree |
| Empirical parameters, such as drillability index, Goodrich drillability, Morris' drillability, specific energy test by instrumented cutting, NTH drillability test, direct cutting testing, etc |

**Figure 2.30** Factors affecting the drillability of rock as per (Yarali and Soyer, 2011)

Yarali and Soyer (2011) studied the relationship between drilling rate index(DRI) and brittleness indices as shown in figure 2.31. Thirty two samples were used in the study, uniaxial compression test, Brazilian tensile strength Sievers' J miniature drill test, were conducted. Brittleness was calculated based on percentage of fines, drilling rate index was calculated by chart based on brittleness index and Sievers' J miniature drill test. DRI also known as drilling rate index was made use of in this study which was used as an indicator of penetration inside the rock and not as an indicator of strength of the rock. DRI was developed in 1950s and has been applied in tunnel boring since 1972 according to Yarali and Kahraman (2010) Thereafter using method of least square regression analysis it was found that there was no significant correlation in between the DRI value and the brittleness index $B_1$ and $B_2$. but, there was a strong negative correlation between the DRI value and the brittleness index $B_3$, $B_4$. procedure for determining brittleness index by Dahl (2003) is shown in figure 2.32

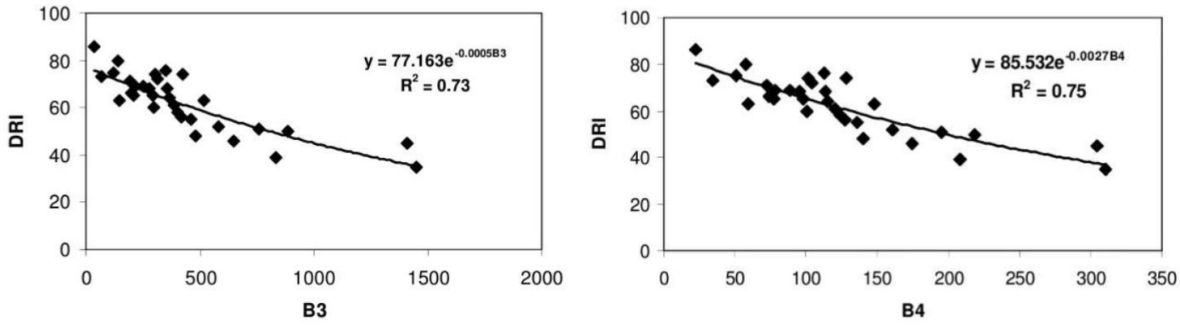



**Figure 2.31** Relationship between DRI and $B_3$ And between DRI and $B_4$ As per (Yarali and Soyer, 2011)

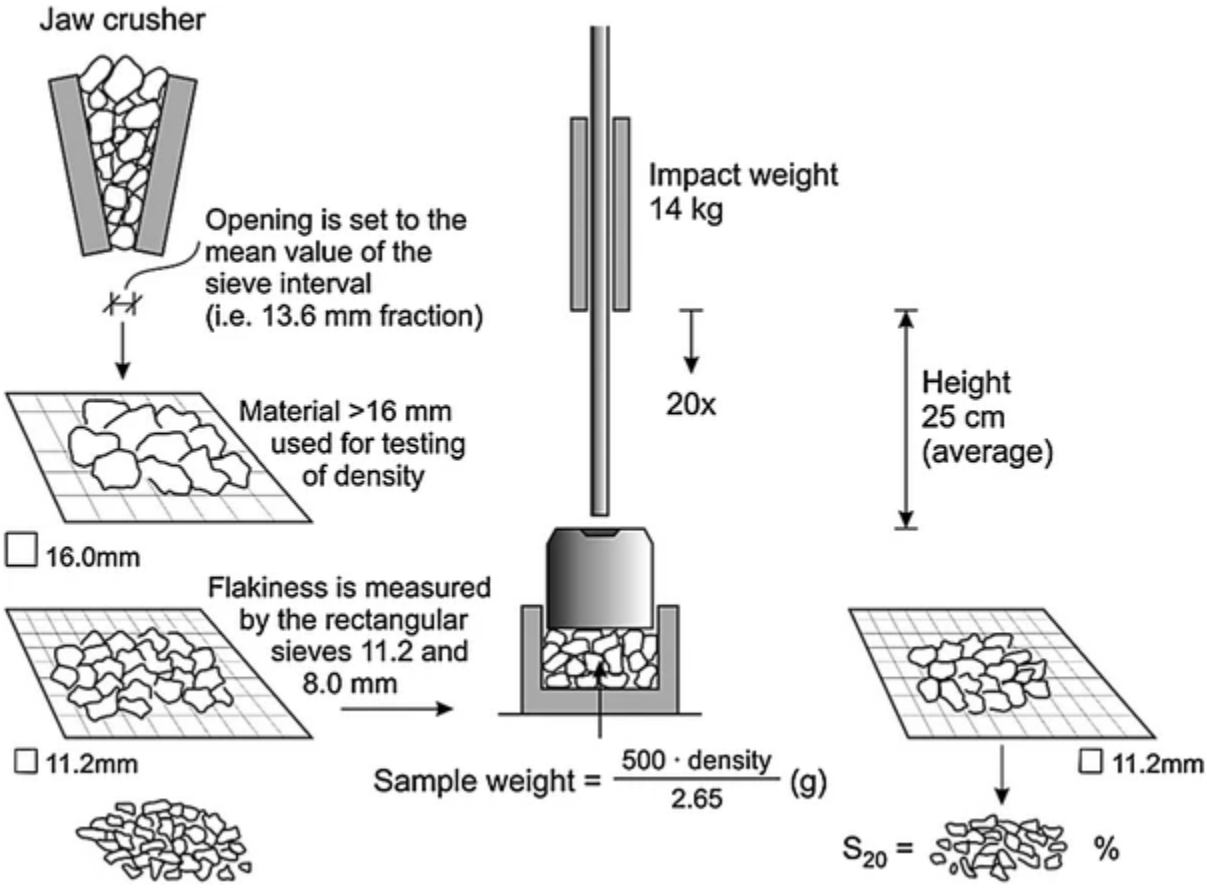

Jaw crusher
Opening is set to the mean value of the sieve interval (i.e. 13.6 mm fraction)
Material >16 mm used for testing of density
16.0mm
Flakiness is measured by the rectangular sieves 11.2 and 8.0 mm
11.2mm
Impact weight 14 kg
20x
Height 25 cm (average)
Sample weight = 500 · density / 2.65 (g)
11.2mm
S20 = %

**Figure 2.32** Determination of brittleness of rock as per (Dahl, 2003).

Yarali and Kahraman (2010) made use of Sievers'J-miniature drill test along with uniaxial compressive strength test and tensile strength test to determine DRI. Sievers J-miniature drill test is basically a measure of surface hardness of rock, it is carried out on an nx size core sample as per the method suggested in NTNU (1998). as per which the bit has to perform 200 revolutions and depth of the drill hole was measured using the electronic micrometer and the test is performed 4-8 times for each rock and average value is taken as the final answer. The brittleness test suggested by Dahl (2003) was made use of. Finally, the least squares regression was used to obtain correlation between DRI and the brittleness index. It was observed that a good correlation was not found between $B_3$ and DRI mainly because of the narrow range but $B_8$ and DRI were strongly Correlated. the relationship between DRI and$B_8$ is as follows $DRI=55.69+ 77.16e^{-0.0005B86}$

**Table 2.10** Category vs DRI as per (Dahl, 2003)

| Category | DRI |
|---|---|
| Extremely low | ⩽25 |
| Very low | 26–32 |
| Low | 33–42 |
| Medium | 43–57 |
| High | 58–69 |
| Very high | 70–82 |
| Extremely high | ⩾83 |

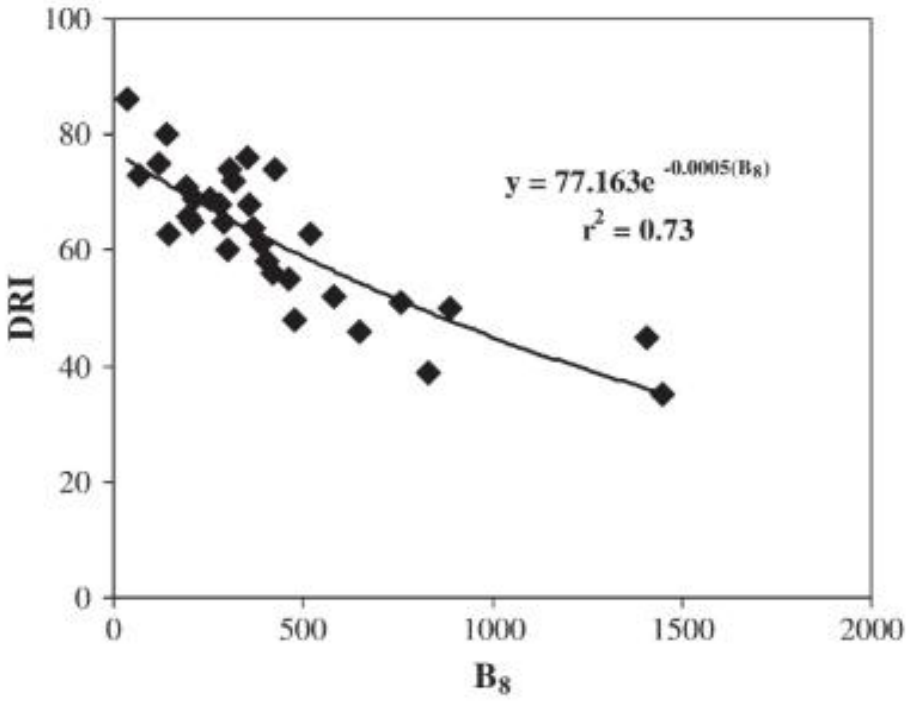



**Figure 2.33** Relationship between DRI and $B_8$ as per (Yarali and Kahraman, 2010)

Yarali and kahraman (2010) also discuss the manner in which DRI values can be computed. Based on the chart presented by Dahl (2003), first one needs to obtain the brittleness values ranging from 0-80 thereafter the DRI has to be computed ranging from 0.5- 150 then by making use of the chart one can obtain the DRI values. From the fig 3.34 it can be observed that corresponding to brittleness value of 52 and siever's J test value of 130 we have our DRI value of around 70. This chart can help us to determine the DRI value for different combinations of inputs. As per Gao et al. (2022) rock brittleness defines the drilling efficiency of the drill rigs associated with TBM tunneling. As per Altindag (2002) specific energy, the

coefficient of rock strength, rock texture are different parameters which are considered in drillability analysis.

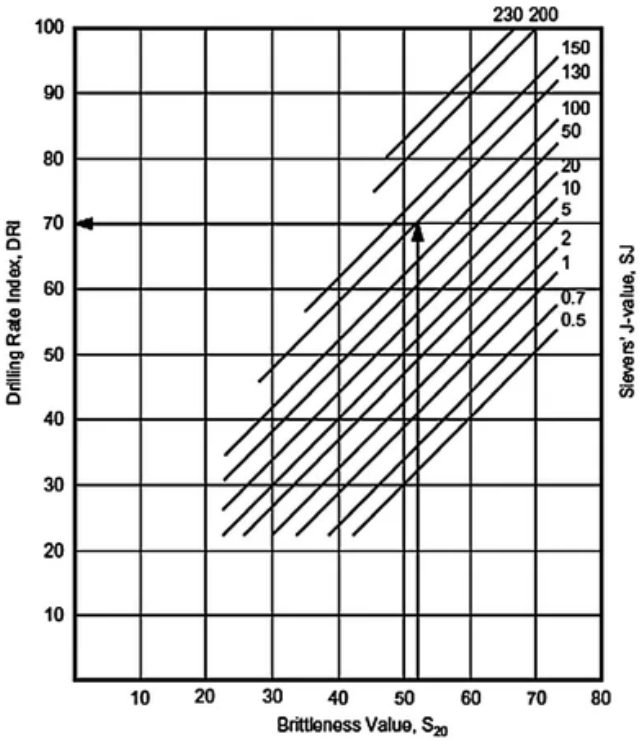



**Figure 2.34** Chart between DRI and siever's j values for different brittleness values as per (Dahl, 2003)

In drillability analysis. The evaluation of rock brittleness concept on rotary blast hole drills was carried out by Altindag (2002) herein drillability index was considered which is same as drilling rate index, various properties were correlated with brittleness index $B_2$ like elastic modulus, point load index and velocity of primary waves etc. correlation between brittleness index and drillability for conical bit tooth and spherical bit tooth was carried out. Herein good correlation was obtained between drillability index and brittleness in case of conical bit tooth and spherical bit tooth. Similarly conical indenters which are used for producing indentation in rock was found to be positively correlated with brittleness index $B_2$ when cone indenter values were plotted against brittleness index $B_2$. Dursun and Gokay (2015) discussed various parameters which affects specific energy these are as follows rock type, rock texture and mineralogy, porosity, density, uniaxial compressive, tensile, and shear strengths, elasticity modulus, Poisson's ratio, rock brittleness, fracture toughness, shore and Schmidt hardness, etc.

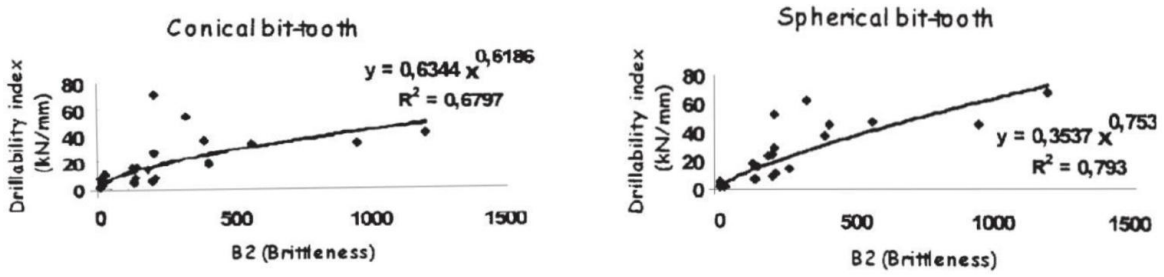



**Figure 2.35** Relationship between drilling rate index and brittleness for conical and spherical tooth as per (Altindag, 2003)

### 2.5.3 Cuttability of rock

Cuttability is an important parameter which is taken into consideration while construction of tunnels as it reflects the performance of cutters used in rock cutting as per Tirayaki (2006). The rock cutting process involves the production of chips from rocks, which is achieved from cracks initiation and propagation thereafter coalescence of these cracks generating chips of rock. Singh (1986) stated that cuttability of coal depends on the brittleness of coal. According to Dursun and Gokay (2015) cuttability can be used to determine specific energy and also it is inversely related with it. Cuttability can be defined as resistance against cutting by mechanical tool such as disc cutters and roller cutters as per Dursun and Gokay (2015). The cutting efficiency of tunnel boring machine was found to increase with brittleness of the rock according to Gong and Zhao (2007). Brittleness is an important property for rock excavation and therefore it is necessary to study the relationship between brittleness and cuttability of rock. Fowell and McFeat-Smith (1976) discussed various methods used for computing cuttability, which were property tests like Brazilian tensile strength, point load strength, uniaxial compressive strength, certain cutting tests, indentation tests etc, these tests are time consuming and expensive. While determining cuttability the various forces acting on the cutters are considered as well as the specific energy consumed in this process. brittleness index defined by Altindag (2003) can be used as a measure of cutting efficiency.

### 2.5.4 Blastability of rock

The term blastability refers to how susceptible the rock mass is to blasting. Brittle rocks have a tendency to develop cracks with little plastic deformation, as a result comparatively lesser quantity of explosives are required for blasting brittle rocks. A brittle rock because of the generation of a network of cracks generates finer fragments, as a result better fragmentation is achieved.

### 2.5.5 Role of brittleness in rock fragmentation process by tunnel boring machines cutters

Gong and Zhao (2007) discussed the influence of rock brittleness on the performance of TBM cutters, therein simulations were carried out using UDEC software, and corresponding plots of brittleness indices were obtained. From the results generated the network of fractures generated corresponding to different values of brittleness indices can be studied. Figure 3.36 shows the brittleness index and crack length.

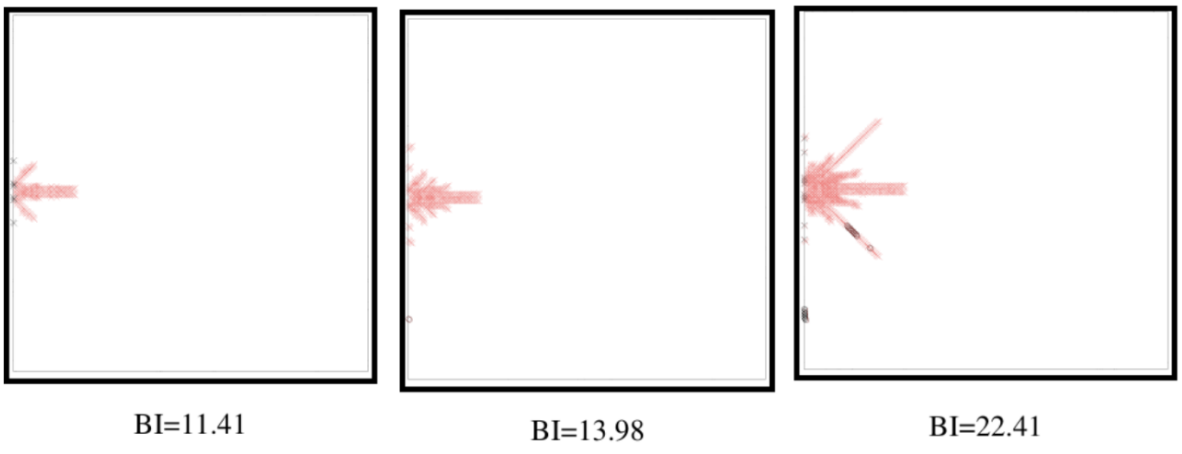



**Figure 2.36** Brittleness index and crack network as per (Gong and Zhao, 2007)

As the value of brittleness index is increasing we can observe the network of cracks increases which is a feature of the brittle rock. So with rise in the brittleness of rock the cutter indentation process becomes easier as per Gong and Zhao (2007). Brittle rock develops tensile fractures whereas brittle rock develops shear fractures. Brittle rocks release energy easily whereas ductile rocks absorb energy. With help of numerical modeling the plot of failure elements and brittleness index was developed by Gong and Zhao (2007) as shown in figure 3.37 .Therein it can be observed that as the brittleness index increases the failure elements also increases this is because of development of extensive cracks within the rock sample. The brittle rocks have the ability to develop extensive cracks. BT represents tensile strength and BI represents brittleness index of granite rock. As the tensile strength is increasing the failure elements are decreasing as the rock now has the ability to handle higher load and as result brittle character is suppressed generating lesser failure elements .

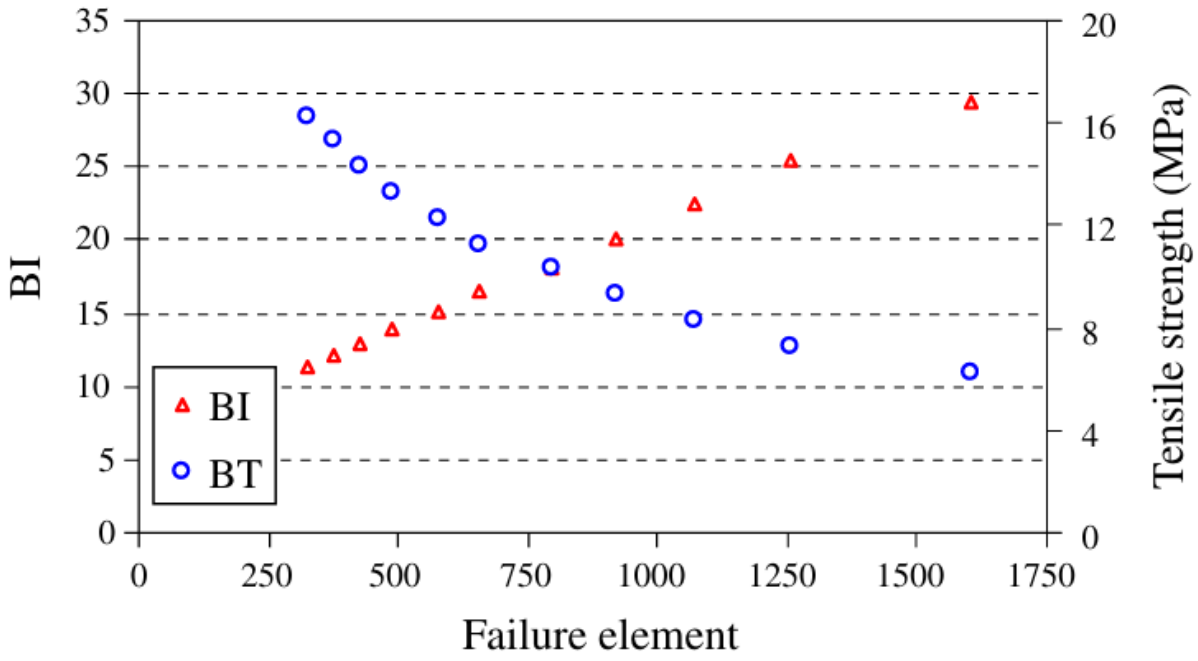



**Figure 2.37** Plot of failure elements and the brittleness index along with tensile strength as per (Gong and Zhao, 2007)

### 2.5.6 Role of brittleness on the penetration rate of tunnel boring machine(TBM)

The penetration rate increases with increase in the brittleness of the rock as per Kahraman (2002). As far as penetration into the rock is concerned, one needs to break the rock in front and advance forward, that is what is understood from penetration. Now in order to break the rock extensive crack formation is important, something which can be achieved by an indenter. If the rock is able to easily develop a network of cracks then it will be easier to form chips and hence the penetration. Therefore higher the brittleness, more will be the cracks formations , more easy would be the penetration within the rock as per Gong and Zhao (2007). from the figure 3.38 it can be observed that for angle between the joint planes and tunnels axis of 20 and volumetric joint count of 10 and different UCS values of 100,200 and 300MPa the penetration rate was highest for lower UCS value and lowest rate for highest UCS values its so because high UCS means more resistance offered by the rock for penetration. Also the specific energy would be higher for high UCS rock and so would be the wear and tear and drill bits, vibrations and the noise generated. lower penetration rate means more time would be consumed in drilling the rock . Gong et al. (2005) discussed other parameters affecting penetration rates like joint spacing and joint orientation. According to Kahraman (2002) the penetration rack decreases with increasing brittleness of the rock.

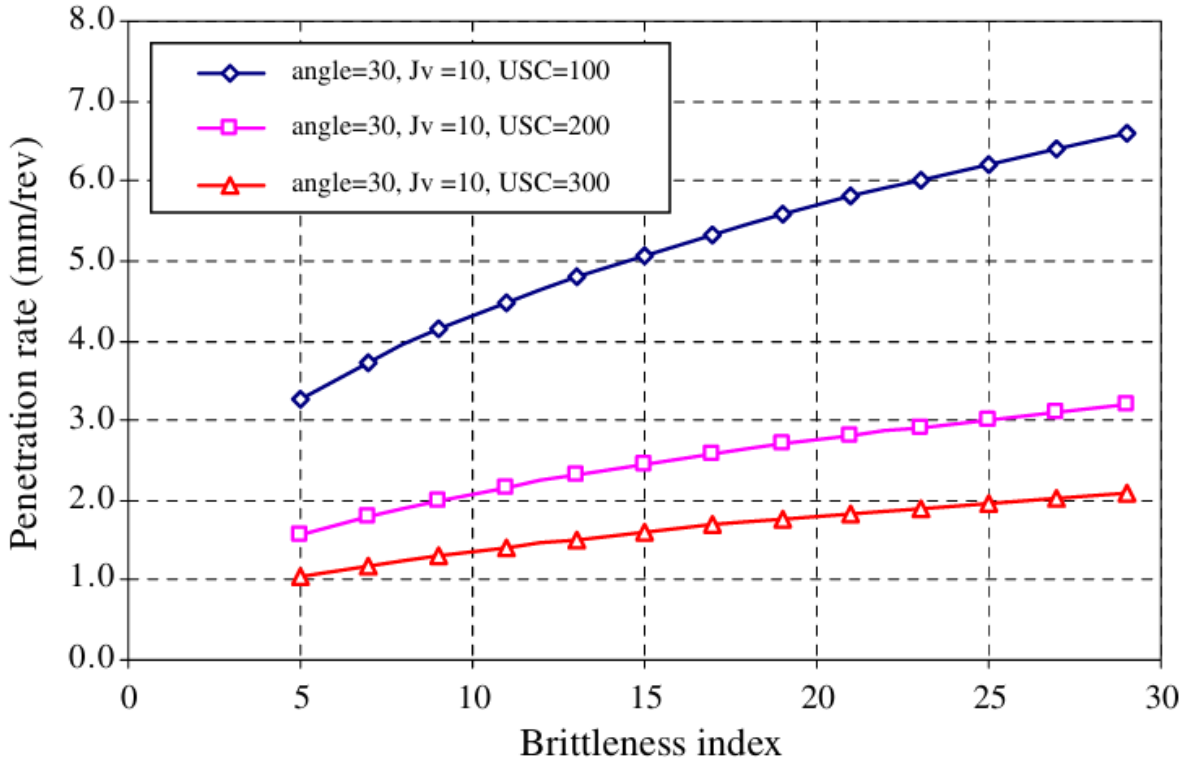



**Figure 2.38** Plot of brittleness index against the penetration rate of TBM for different values of volumetric joint count and UCS as per (Gong and Zhao, 2007)

## 2.6 Role of brittleness on borehole stability

As per Holt et al. (2015) ductile deformation is favourable for borehole stability as compared to brittle deformation, because of loss of load bearing capacity of the host rock. However in case of brittle rock situations like borehole collapse can occur which will eventually cause closing of the borehole. Brittle rocks generate a wide network of cracks and generate more fragments around the borehole wall, which will eventually fall in the hole causing its closure. Zhang et al. (2022) stated that borehole stability is actually a mechanical instability and is the key issue in drilling through shale formation for hydraulic fracturing. Holt et al. (2015) stated that drilling fluid has a huge role to play in borehole collapse.

### 2.6.1 Role of brittleness on boreability

As per Li et al. (2024) the abrasiveness, strength, brittleness are amongst the most important factors affecting the boreability of rock during the tunneling operation using tunnel boring machines; similarly when brittleness of rock increases, the boreability of rock decreases. Gong and Zhao (2007) reported negative correlation between boreability of rock and brittleness index

$B_1$.Similarly brittle rocks require less energy for boring the rock as compared to non brittle rock.

## 2.7 Role of brittleness in fracture toughness

Kahraman and Altindag (2003) made use of brittleness index $B_4$ to predict the fracture toughness of rock. Altindag (2003) Obtained positive correlation between brittleness index $B_4$ and fracture toughness of the rock. Nejati and Moosavi (2017) studied the relationship between brittleness index $B_4$ and fracture toughness as shown in figure 3.39. good correlation was observed in between mode two fracture toughness and brittleness index $B_4$

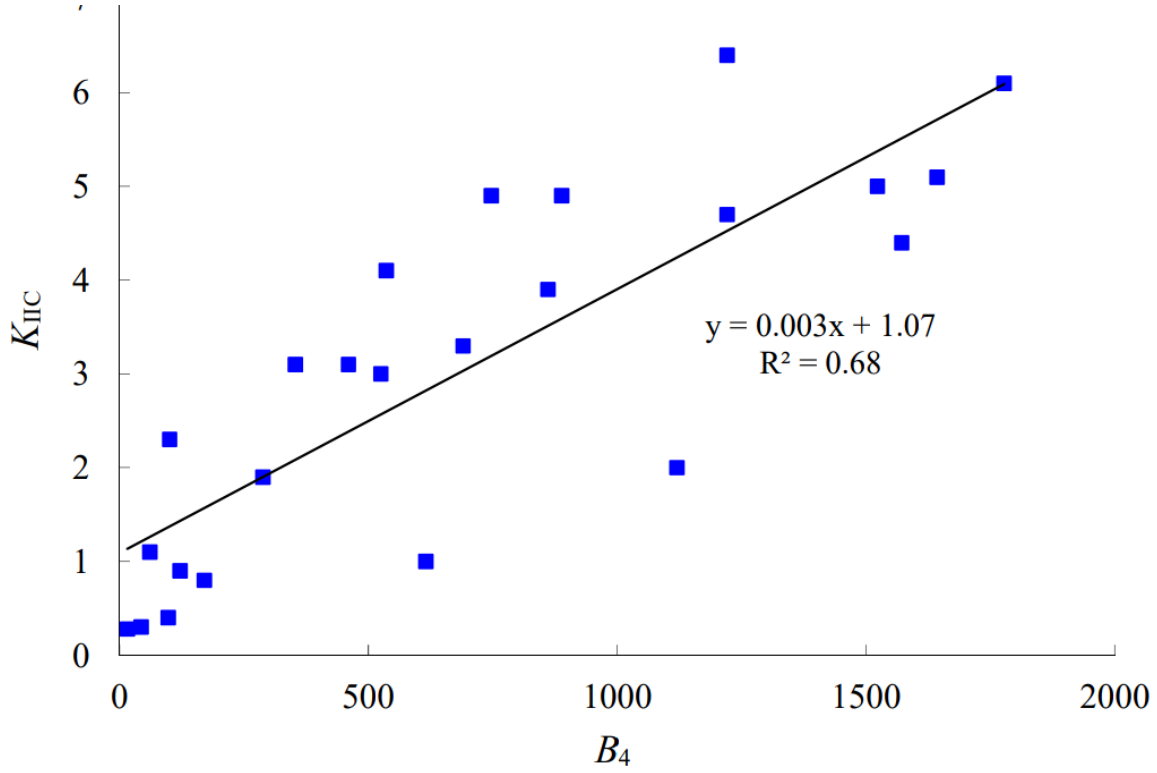



**Figure 2.39** Relationship between mode two fracture toughness and brittleness index as per (Nejati and Moosavi, 2017).

## 2.8 Shale gas extraction

With the rise in consumption of fossil fuel and increasing level of pollution because of the same, search for alternative sources of energy is evident which can support populations and economies around the world,shale gas reservoirs offer a great alternative for the same. This being a clean source of energy is something which is much sought after. unconventional reservoirs hev the potential to make significant contribution to the hydrocarbon production across the world but there are challenges as the gas flow rate for unconventional reservoirs are less.

According to Liu et al. (2024) shale gas can be found in different parts of the world including Central Asia, North America, Middle East,China and North Africa , amongst them China had the largest reserves. Shale gas reservoirs are categorised by lamellar structure,fine grain size,thin single-layer thickness and high organic content as per Ye et al. (2018).

This gas is found trapped under sedimentary rocks, within the pores, they are unconventional in nature as we need to apply external energy in order to extract the gas from its place. Brittleness being a mechanical property of rocks as per Meng et al. (2020) ,is very important for profitable extraction of shale gas. Basically the shale gas reservoir has very low porosity and permeability initially as per Ye et al. (2020), as a result making use of hydraulic fracturing becomes a necessity.

Hydraulic fracturing enhances the fracture network in the strata by reopening the natural features and enhancing connectivity between isolated pores within the strata. In hydraulic fracturing , a pressure fluid is injected into strata at high pressure as a result a network of cracks are developed within the strata , these cracks connect isolated pores and increase connectivity between pores so that the shale gas can move towards well bore as per Zhang et al. (2016).

For hydraulic fracturing of tight Reservoirs, the most important thing is to determine whether the rock can be fractured at particular pressure; the injectivity tests are usually performed to ensure the Formation breakdown as per Bai (2016). This actually enhances the movement of gas through strata. Now not all rocks respond equally to hydraulic fracturing, there are some rocks within which the fractures close themselves quickly while in others it remains open, therein comes the importance of brittleness. Actually brittleness helps us to identify Sweet spots for carrying out hydraulic fracturing, so that a complex fracture network can be developed for extraction of gas. Such a network is easy in development in case of brittle rocks. brittleness is linked with well wall stability and reservoir rock drillability according to Xu et al. (2022). The composition and pore structure of shale is important as this determines the gas storage potential of shale according to Ross and Bustin (2009). According to Lie et al. (2023)brittleness is important for selection of staged fracturing and clustering, in oil fields brittleness is evaluated based on logging data and not on basis of stress strain curve as a result parameters from logging like mineral distribution, porosity, density, elastic module, Poisson’s ratio, confining pressure and bedding angle are considered. Factors affecting the brittleness of shale were as follows

1)Mineral composition- higher the content of brittle minerals like quartz more would be the brittleness of rocks similarly higher content of mineral likes clay lower would be brittleness of rock per Liu et al. (2024)

2)Rock structure as per Liu et al. (2024)

3)Diagenesis as per Liu et al. (2024)

4)State of stress as per as per Liu et al. (2024)

### 2.8.1 Role of brittleness in gas extraction

As per Gao et al. (2022) the brittleness of rock is the key element in the evaluation of the reservoir,it is also associated with wellbore stability and creation of fracture network. Brittleness plays an important role in selection of target shale gas extraction as per Holt et al. (2015). Also it has a role to play in identification of fracture intervals in reservoir rock as per Ye et al. (2020). Gas cannot be extracted profitably without fracturing the rock, because shale gas reservoirs have very low porosity and permeability initially as per Ye et al. (2020). Drilling problems occur during extraction of gas as stated by Holt et al. (2015). Rybacki et al. (2015) stated that hydraulic fracturing is done in multiple stages for enhanced production. Brittleness along with fracability both are very important for shale gas extraction as per Tang et al. (2016). Rybacki et al. (2016) categorized mechanical behaviour of shale in two categories namely brittle shale and ductile shale, brittle shale can develop fractures easily after application of hydraulic fracturing and these fractures do not close quickly whereas ductile rocks do not form fractures easily and these fractures tends to close themselves with time much quickly as compared to fractures developed in brittle rocks as per Ye et al. (2020). rocks with higher values of Young's Modulus and low values of Poisson’s ratio are considered to be more brittle as per Liu et al. (2024). Holt et al. (2015) related hydraulic fracture initiation with the in situ stress rather than rock strength.

Brittleness indices based on mineralogical composition is used for determining the brittleness of shale. However Liu et al. (2024) Discussed two different approaches for determining the brittleness index of rock for application in shale gas extraction, first one based on mechanical properties and second one based on mineralogical composition. The brittleness index based on mechanical properties is represented by $(\sigma_p-\sigma_{res})/\sigma_p$ , herein $\sigma_p$ Represents the peak intensity and $\sigma_{res}$ represents the residual strength. The value of the developed index ranges from 0-1,wherein higher values indicates brittle rock. Lie et al. (2023) discussed the role of brittleness in the extraction of shale gas, the techniques used for extraction namely horizontal drilling and

hydraulic fracturing relies heavily on the mechanical properties of shale, similarly the drilling design, wellbore stability relies on the compressive strength of shale, The tensile strength and fracture toughness affects the fracture initiation and propagation. Verma et al. (2016) stated that organic content plays an important role in determining the brittleness of formation as well as in identification of sweet spot for gas extraction; the area having ductile rock have high organic content as a result one can identify which area have brittle and which one has a ductile formation and brittle formations are mostly favoured for gas extraction.

## 2.9 $CO_2$ geosequestration

With the rise in the consumption of fossil fuel $CO_2$ content in the atmosphere has been on rise which has resulted in global warming, which presents a threat to people around the world. Bashir et al. (2023) stated different sources of emission of $CO_2$, namely direct emission like through extraction, transport of fossil fuels as well as through refining, indirect ones are Through production of electricity and other indirect emission including activities linked to $CO_2$ productions indirectly. The $CO_2$ emissions around the world had nearly doubled in the last two decades according to Ali et al. (2021).

This has led to rise in average temperature of places around the world, causing changes in the weather pattern. Therefore in order to improve the situation excessive $CO_2$ present in the atmosphere have to be reduced, one of the way can be $CO_2$ geosequestration as per Ali et al. (2021).Similar other approaches that can also be used for $CO_2$ storage includes wind power, geothermal energy, hydrogen production and carbon free solar panels as per Herrero et al. (2016).

For commercial scale storage of $CO_2$ on a large scale, confinement is very important as per Kaldi et al. (2013), herein the presence of caprock as well as any fault in the caprock must be considered. Kaldi et al. (2013) also discussed seal capacity, seal geometry and seal integrity; the seal capacity can be defined as the height of $CO_2$ column that can be supported by the seal without getting cracked; the seal geometry refers to the lateral extent of the seal, the lateral extent of the seal should be greater than throw of the fault if its present;seal integrity is based on the geomechanical properties of the caprock. The underground storage of carbon dioxide is called $CO_2$ geosequestration. It is stored in salt cavern, aquifer, depleted oil and gas reservoirs as per Ali et al. (2021). The $CO_2$ present in the atmosphere is converted into liquid form and thereafter stored underground as per Ali (2018). Ali et al. (2021) mentioned different trapping mechanisms like hydrodynamic trapping which is prominent in sedimentary formation

and caprock, adsorption trapping which is prominent in coal seam and Organic rich shale and residual trapping prominent in sedimentary formation. $CO_2$ wettability is the most important factor under consideration for $CO_2$ geosequestration as per Ali et al. (2021). Formations that are less water wet would offer low $CO_2$ storage potential as per Chaudhary et al. (2013).

### 2.9.1 Role of brittleness

The caprock which is the rock above the reservoir that acts as a seal above the reservoir plays an important role in this process. As per Kaldi et al. (2013) caprock and presence of fault are two most important factors in $CO_2$ sequestration. Understanding porosity and permeability of reservoirs are important. The brittleness of reservoir and cap rocks is important to ascertain their integrity for $CO_2$ storage This is because when $CO_2$ would be injected at high-pressure underground, then brittle rock would generate more fractures, as a result leakage of $CO_2$ can occur. Petrophysical, geochemical and geomechanical properties of the caprock and reservoir rock changes because of leakage of $CO_2$. The role of cap rock is to seal the $CO_2$ within the reservoir, Ideally the cap rock should not be brittle and permeable. An example of good caprock is shale. Different locations for storage are shown in figure 2.40 .

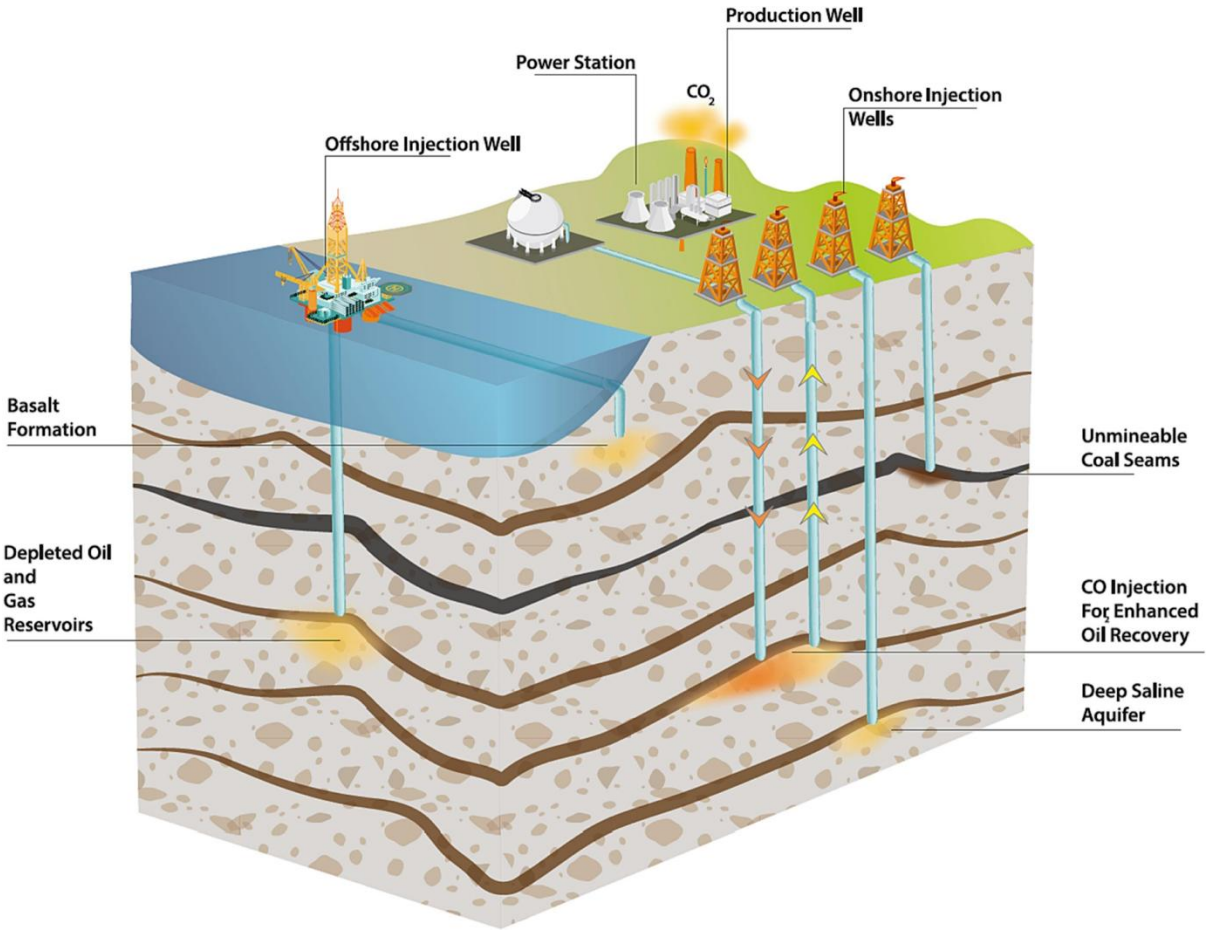



**Figure 2.40** Locations for $CO_2$ geosequestration as per (Ali et al., 2022)

## 2.10 Rockburst

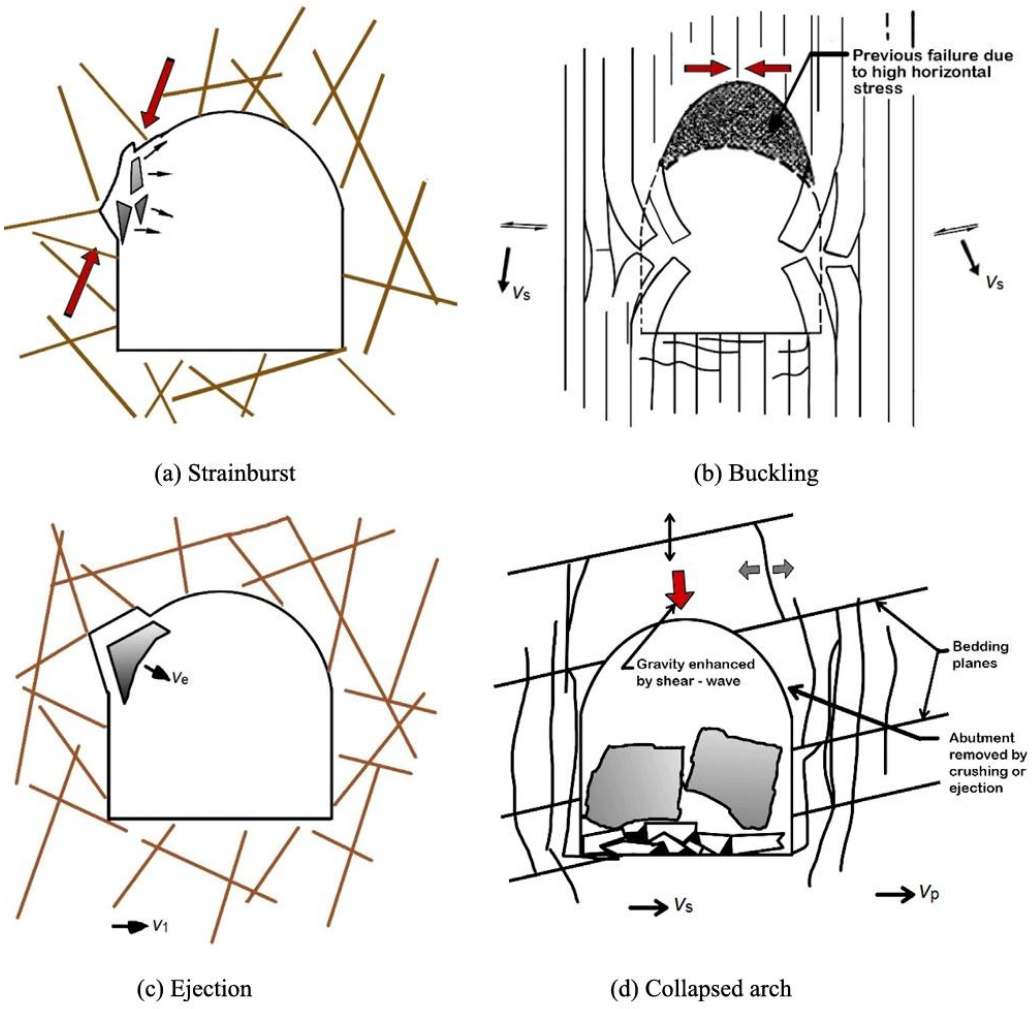
With Rise in demand for minerals around the world, mining has shifted towards greater depth. But with this development comes new sets of challenges. Greater depth means high stress and high temperature as well. rock behaves differently under these conditions as it's a well known fact that temperature affects the mechanical properties of rocks. Along with these factors such as strength and brittleness, magnitude of in situ stresses, dynamic disturbance, excavation sequence and geological structure affects the rock mass instability as per Meng et al. (2017). As a result excavations carried out at greater depth present hazards like rockburst, rockburst encountered during jinping-II headrace tunnels project is shown in figure 2.41. Terzhagi (1946) defined rockburst as falling rock from the surface of a tunnel wall made up of hard brittle rock. A rockburst is a violent failure of rock associated with ejection of particles at very high velocity along with seismic events as per Akdag et al. (2018). Xu et al. (2021) defined rockburst as a geological disaster caused by excavation in hard brittle rock under high Geo stress environment. Askaripour et al. (2022) defined rockburst as a specific type of rock mass

failure in hard and brittle rock around the excavation. Lu et al. (2018) stated that presence of geological structure such as fault may cause rockburst. Yang et al. (2017) stated that high insitu stress as the main causative factor for rockburst. Zhu et al. (2010) laid more emphasis on dynamic disturbance as a causative factor for rockburst. Rockburst are classified based on different parameters like Ortlepp and Stacey (1994) used rockburst intensity and triggering mechanism as criteria for rockburst classification, Also rockburst were classified on the basis of the source and damage mechanisms. Hedley (1992) classified rockburst as inherent, induced and Fault slip Burst. Askaripour et al. (2022) classified rockburst as strainburst ,pillar burst , ejection and Fault slip Burst as shown in figure 2.42.

**Figure 2.41** Rockburst encountered during jinping-II headrace tunnels project as per (Zhou et al., 2014).

Role of brittleness is important in prediction and prevention of rockburst. Cai (2015) made use of energy analysis for rockburst prediction, the presence of high stress environment and ability to store huge amount of energy were two essential conditions for rockburst. The energy dissipated during plastic deformation lowers down total energy content but in case of brittle failure,very little plastic deformation occurs as a result huge amount of energy gets released in form of brittle failure in short span of time generating rockburst. Rocks with high brittleness

index are more likely to experience rockburst. Brittleness controls the mechanical behaviour and failure characteristics of rock. Monitoring microseismic activity in areas with brittle rocks can provide early warning of impending rockbursts, allowing for timely adjustments to mining operations. Understanding the brittleness of the rock mass helps in selecting appropriate rock support systems. For example, in highly brittle rocks, a more rigid support system with expansion shell bolts or end-grouted rockbolts might be preferred.




(a) Strainburst (b) Buckling

(c) Ejection (d) Collapsed arch

**Figure 2.42** Different types of rockburst as per (Askaripour et al., 2022)

### 2.10.1 Role of brittleness in rockburst

The disaster of rockburst occurs because the rock has the ability to store huge amounts of energy and secondly release the accumulated energy in a very short span of time. The strength of rock also has a role to play herein as the accumulated energy within the rock is a measure of strength of rock, higher the strength more would be the accumulated energy , more the energy accumulated more would be the energy release and more would be the severity of rockburst hard rock have the ability to store huge amount of energy because of high strength and the brittle failure by definition showcases a sudden fall in stress strain curve post peak stress accompanied by sudden loss in load bearing capacity as a result the rock failure occurs. The sudden loss in strength can be attributed to the fact that a network of fine cracks are developed throughout the rockmass, these cracks thereafter coalesce with one another developing another set of cracks which occurs very instantaneously and produces sudden loss in strength. The same is not true in case of ductile rocks as they have the ability to undergo deformation or change in shape which acts as a medium for energy dissipation and ductile rocks do not showcase development of fracture network as a result their failure is not as violent as brittle rock. Brittleness is actually a behaviour of rock which is reflected by the deformation characteristics of rock, the rock which fails to change itself under unbearable conditions fails and displays brittle failure whereas the one which undergoes deformation under such conditions undergoes ductile failure as per Meng et al. (2020).From the perspective of energy, deformation meaning change in shape, consumes energy thereby reducing the total energy count within the rock, as result the rock does display ejection of particles, noise which are characteristic features of brittle rocks. Understanding of brittleness is important from perspective of handling situation like rockburst as per Tarasov and Potvin (2013).

Brittleness is considered for categorizing rockburst, Wang and Park (2001) categorized rockburst based on brittleness index $B_1$ herein referred to as rock brittleness coefficient is based on strength parameters, Risk of rockburst intensity based on brittleness coefficient is as shown in table 2.11. Neyman et al. (1972) used brittleness deformation index which is ratio of tensile strength and maximum insitu stress component for categorizing rockburst as shown in table 2.12.

**Table 2.11** Risk of rockburst intensity based on brittleness coefficient as per ( Wang and Park., 2001)

| Rock brittleness coefficient | Risk of violent rupture |
|---|---|
| $B_i > 40$ | No rockburst |
| $26.7 < B_i < 40$ | Weak rockburst |
| $14.5 < B_i < 26.7$ | Moderate rockburst |
| $B_i < 14.5$ | Strong rockburst |

**Table 2.12** Intensity of rockburst based on brittleness deformation coefficient as (Neyman et al., 1972)

| Brittle deformation coefficient | Rockburst intensity |
|---|---|
| $K_u \leq 2$ | No rockburst |
| $2 < K_u \leq 6$ | Light rockburst |
| $6 < K_u \leq 9$ | Medium rockburst |
| $K_u > 9$ | Strong rockburst |

Zhang et al. (2003) Also made use of rock brittleness coefficient for categorizing rockburst, higher the values of the index more would be the severity of the rockburst, table 2.13 shows the risk associated with value is rock brittleness coefficient. Table 2.14 shares the classification by Tang and Wang (2002)

**Table 2.13** Prediction of risk of rockburst based on rock brittleness coefficient as per (Zhang et al., 2003)

| Rock brittleness coefficient | Risk of violent rupture |
|---|---|
| $B_i < 10$ | No rockburst |
| $10 < B_i < 18$ | Weak rockburst |
| $B_i > 18$ | Strong rockburst |

**Table 2.14** Prediction of risk of rockburst based on rock brittleness index as per (Tang and Wang., 2002).

| Rock brittleness index | Risk of violent rupture |
|---|---|
| $K \leq 20$ | No rockburst |
| $20 < K \leq 75$ | Light rockburst |
| $75 < K \leq 130$ | Medium rockburst |
| $K > 130$ | Strong rockburst |

## 2.11 Underground nuclear repository

The safe disposal of high level radioactive nuclear waste was considered necessary for the future of the nuclear industry as per Chen et al. (2023). They are a facility, constructed for disposal of nuclear waste deep within the ground and are constructed as a series of rooms for storing waste canisters.Their depth may range from 200-1000m. Crystalline rocks like granite are considered ideal for underground nuclear waste storage, because of their low permeability and ability of good retention capability for nucleotides. When hot nuclear waste is stored underground, the heat may transfer into surrounding rocks, generating thermal stresses in surrounding rocks . But since granite is a brittle rock, the stresses will cause crack generation in rocks as a result the radioactive particles would get out and spread in surrounding areas.India is actively developing a deep geological repository for permanent nuclear waste storage at Tarapur.A typical under underground nuclear repository is shown in figure 2.43.

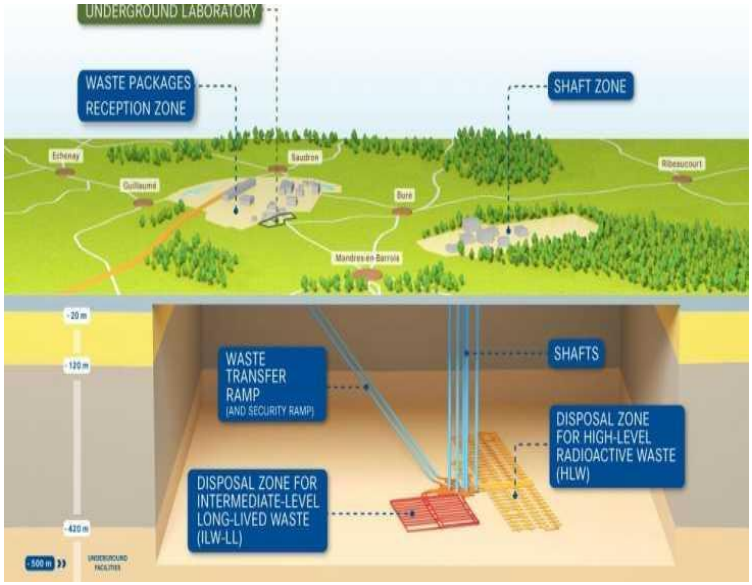



**Figure 2.43** A typical under underground nuclear repository

# CHAPTER 3
# METHODOLOGY

## 3.1 **Rock sample**

The rock considered for the study was Chunar sandstone, it is a fine grained sedimentary rock obtained from Mirzapur district of Uttar pradesh. It is reddish or buff coloured and has extensive known applications in Indian Architecture. It is known to maintain a smooth texture despite immersion in water. The Fort of Chunar and Fort of Ramnagar are made up of Chunar sandstone. It has received GI tag in 2019 recognising its unique characteristics and origin. It is durable and hard in nature. Its physical chemical and mechanical composition is almost uniform. It can be fine grained or medium grained.

## 3.2 Sample preparation

Sample preparation involves the process of generation of a workable sample from rock. Different processes like coring, crushing, grinding are involved to shape the samples as per ASTM D7012-23 for UCS and triaxial tests. Chunar sandstone was available in form of large blocks, they were first introduced to the coring machine in order to obtain core logs. Core logs were long cylindrical shape logs of rocks obtained with help of core bits. Diamond core drill bit was used for Chunar sandstone. The drill bit had diameter of 54mm and core logs obtained had length of around 20-22cm. DD 160 core drill from Hilti was used for obtained core logs, it offered 2 different gear systems offering 740 rpm speed. Thereafter the logs were subjected to a core cutting machine by Aimil. Through this the UCS and BTS samples were obtained. The surface needs to be levelled hereafter so the samples were subjected to a grinding machine by Aimil having a grinding wheel. The machine is designed to cylindrical rock specimens upto 150mm. The outfit includes a diamond impregnated cutter, a fine grinding wheel and sample holder. The samples were subjected to this grinding wheel and grinded. The different steps are shown in figure 3.1.

a) b) c) d) e)

**Figure 3.1** Different steps in sample preparation a) Coring b) Cutting c) Grinding d) Taking Measurements of Dimension e) Taking Weight of samples

Thereafter vernier calliper was used to measure dimensions of samples, so that density can be computed. Henceforth weight was computed by placing samples onto the weighing machine and readings were taken. All the data generated was carefully noted. Thereafter sets of samples were generated. One set of sample will include a single UCS sample, three triaxial samples and three BTS samples. The first set was at 25°C henceforth referred as RT or room temperature. The next set samples was for temperature of 200°C, 300°C, 400°C, 500°C,600°C. The rate of temperature increase will be 2 C. This low rate of heating is used to keep the thermal gradient as small as possible and to ensure that the cracking process is induced by the temperature effect only and not by the thermal gradient through the sample. The sample is kept at the target temperature for 4 hours so that the grains reach the target temperature. The samples were heated in a furnace. Cooling : Slow cooling in the furnace for 24 hours. Then again the measurements of samples were taken and readings were noted down.

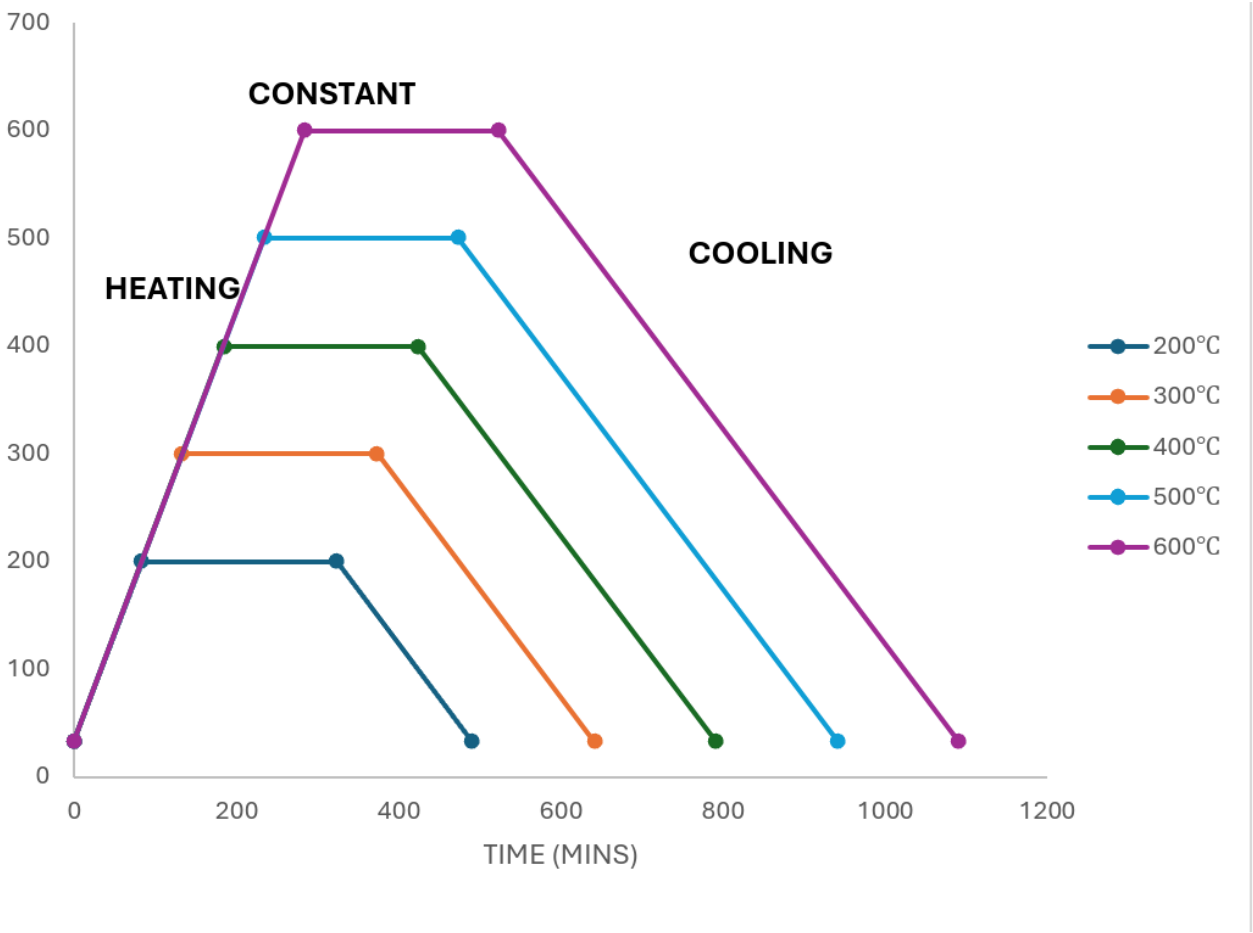



**Figure 3.2** Temperature and time showing heating and cooling period

Figure 3.2 Reflected the temperature along with the heating and cooling period with time on one axis and temperature onto other. Figure 3.3 reflects the methodology i.e. the step by step approach adopted for the study. It starts from literature review and ends when analysing of the data generated was completed.

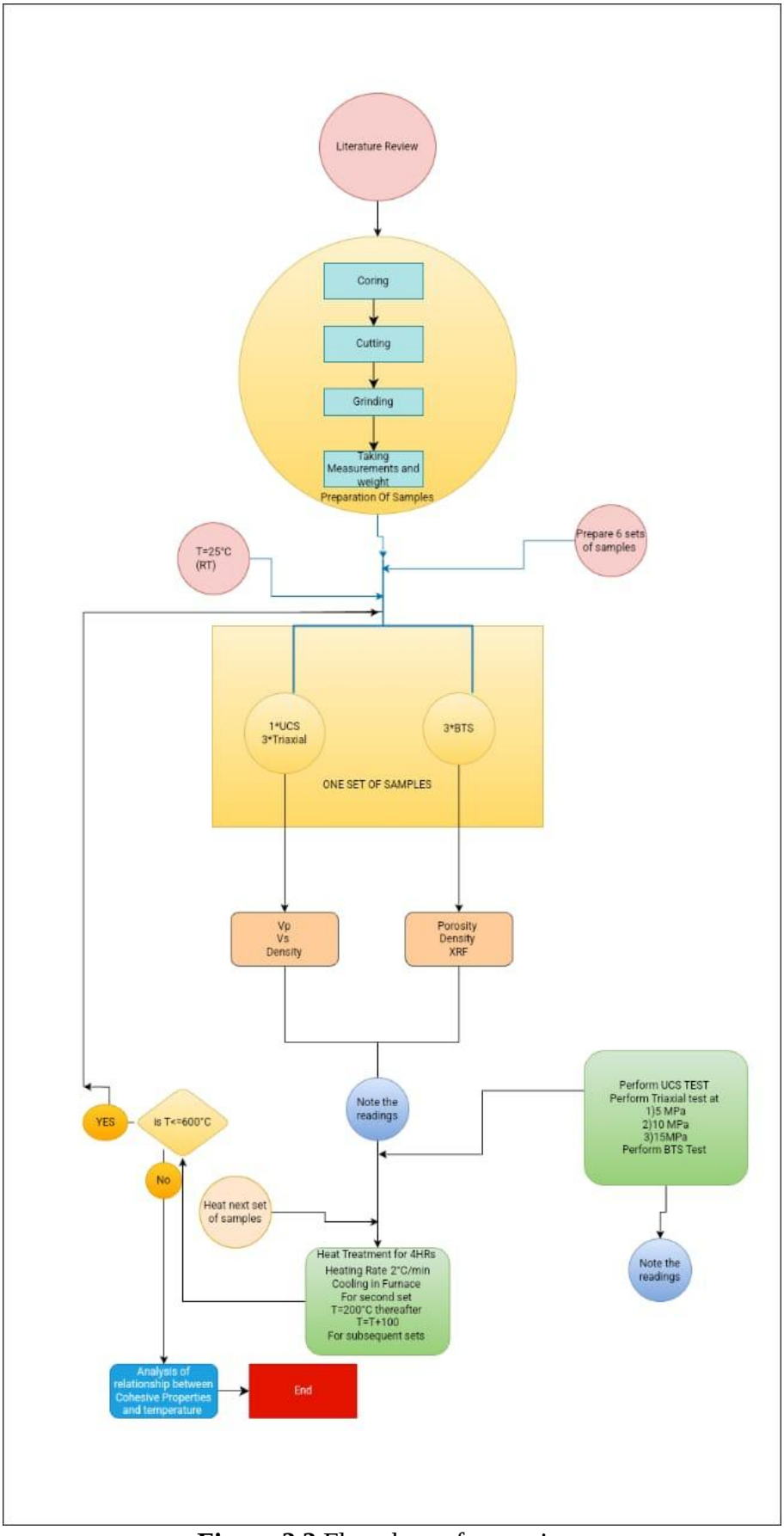



**Figure 3.3** Flowchart of operations

## 3.3 Porosity

Porosity is a very important physical property of rock. It's expressed as the ratio of volume of void to total volume. Porosity is a dimensionless quantity and is expressed in the form of percentage. Porosity can range anywhere from 0% to 100% .Porosity can be defined as the ability of rock to store water. More porous the rock ,the more water the rock can hold. rocks are composed of mineral grains and it is in the packing of these grains which give rise to voids within the rock matrix. Now these voids can be isolated or connected to one another. The ones which are connected to one another give rise to permeability of rock. Following the general trend, sedimentary rocks generally have high porosity as compared to igneous and metamorphic rocks. Porosity can be classified as absolute porosity ie pores are not interconnected or effective porosity ie pores are connected. Porosity can also be classified as primary or secondary based on formation of pores during deposition of sediment and after they are deposited.

The porosity was determined using BTS samples. Herein the dry weight was calculated by placing the BTS Samples on an electronic weighing machine. Then submerged weight was computed wherein the samples was kept submerged within the water and weight was computed using the electronic weighing machine. thereafter the BTS samples were kept submerged in water for 24 Hr during this process the pores will get saturated with water and thereafter the saturated weights were computed, different steps are as shown in figure 3.4.

Porosity can be computed using the formula stated below

**Figure 3.4** Different steps in determining the porosity of the Chunar sandstone

$$\text{Porosity (\%)} = \frac{\text{Saturated weight(g) - Dry weight (g)}}{\text{Saturated weight(g) - Submerged Weight(g)}}$$

The values of porosity for Chunar sandstone can range from 10% -19%.

## 3.4 Primary and secondary wave velocity

Body waves are categorised as compressional waves or P waves and shear waves or S waves. These waves have different properties like the P waves velocity of rock is always higher than that S wave velocity. They are expressed in m/sec. P waves can pass through all three states of matter whereas S waves can pass only through Solids. The velocity measurement was based on ultrasonic pulse technique, which involves generation and propagation of waves through the material and calculation of time taken for propagation of waves through the material. The pulse generator with help of transducers generate ultrasonic waves, then these waves travel through the sample and received at receiver end. Initially the equipment has to be calibrated both for Vp and Vs measurements. Then since length of sample is known the velocity can be computed based on simple kinematical equation of velocity. Using the ratio of these velocities, different mechanical properties of rocks such as Poisson's ratio, young's modulus. The velocity of the waves were measured using Punditlink ultrasonic instrument as shown in figure 3.5.The entire tool kit consists of consisting of: Display unit, 2 transducers (54kHz), 2 BNC cables 1.5 m, couplant, calibration rod, battery charger with USB-cable, 4x AA(LR6) batteries, data carrier with software, documentation and carrying case. Transducers are attached to the equipment which acts as a source of waves emission and reception. These transducers are different for P waves and S waves measurements. 54 Khz was the operating frequency in P wave velocity measurements and 37 Khz in S wave velocity measurements. The instrument has a range of 0.1 – 9999 µs Auto ranging and resolution of 0.1 µs. It also has a 79 x 21 mm passive matrix OLED display ,Bandwidth of 20 kHz – 500 kHz. The Initial step consists of attachment of display units and cables along with transducers. Thereafter calibration is required after this the Punditlink software is opened and measurements are taken.

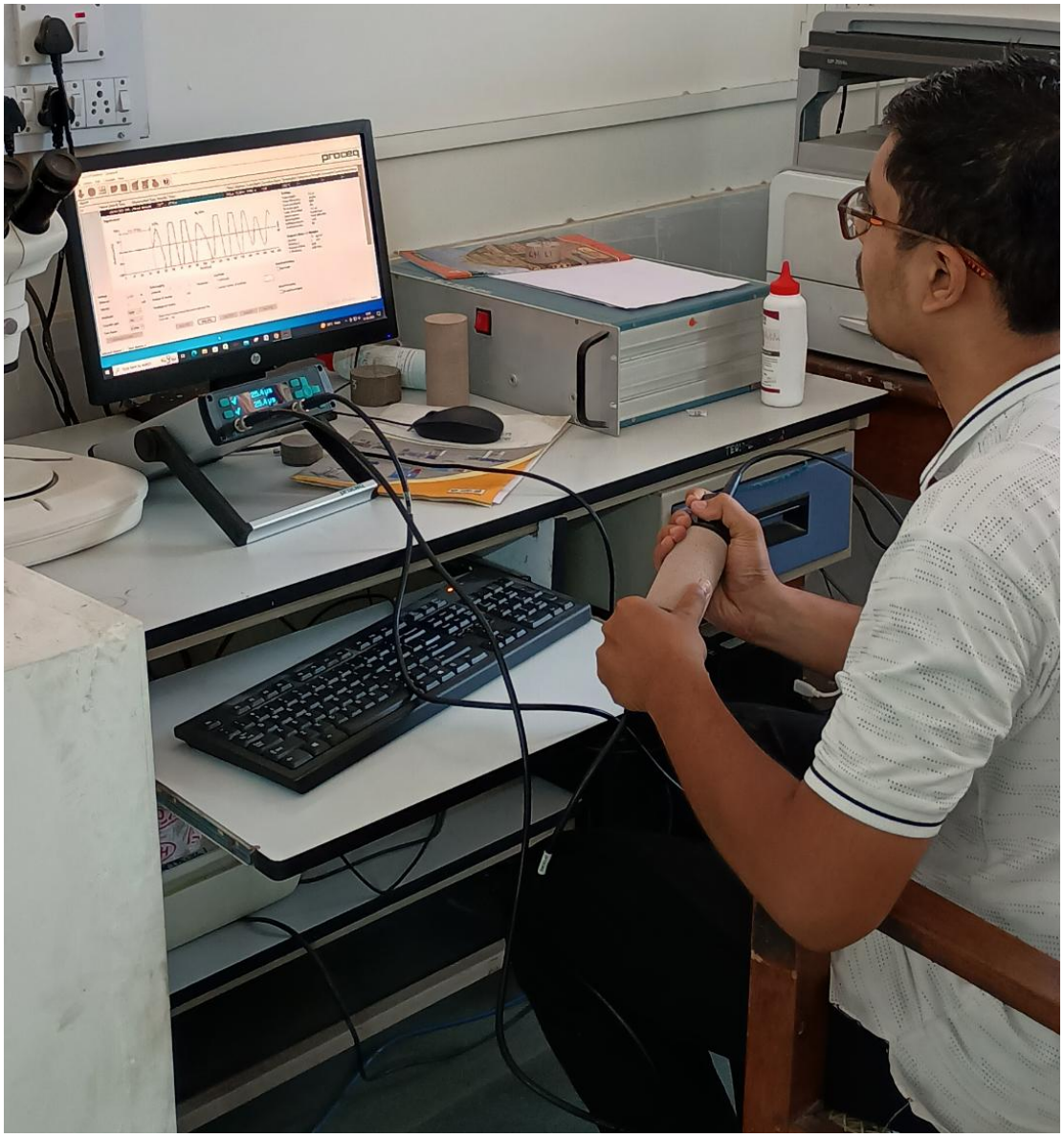


**Figure 3.5** Computing wave velocities

## 3.5 Uniaxial compressive strength test

UCS is a mechanical property of rock and is a measure of strength of rock. It is usually expressed in MPa. In this test load is applied along the longitudinal axis. The sample required for performing UCS test should be prepared as per ASTM D7012 standards according to which the length to diameter ratio should be 2.0-2.5. The ends of the sample must be levelled within a tolerance of 0.02 mm, and the vertical axis must be within 0.06 degrees. The UCS test was carried out using ADVANTEST 9 ROCK advanced testing system which was designed for rock testing. It is suitable for extremely variable materials, from soft sandstone to high-strength marbles. ADVANTEST ROCK performs loading-unloading ramps and can also be used for load/stress/displacement/strain controlled testing. It has maximum working pressure of 700 bar, maximum oil delivery of 2 lpm at low pressure, 0.7 lpm at high pressure and 4 hydraulic

ports for connection of test frames. Its hardware specification includes load sensors (load cells or pressure transducers), displacement transducers (potentiometric, LVDT amplified or analogical) and deformation transducers (clip gauge, strain gauge). ADVANTEST 9 ROCK is linked to a PC for data acquisition and results elaboration. The overall test information and readings are always available on the PC screen. The test was performed on 18 samples, the steps are as shown in figure 3.6, which included 6 batches having 3 samples each; all these batches were subject to different temperature ranges from 100–600°C, starting from 100°C with increment of 100°C in succession.

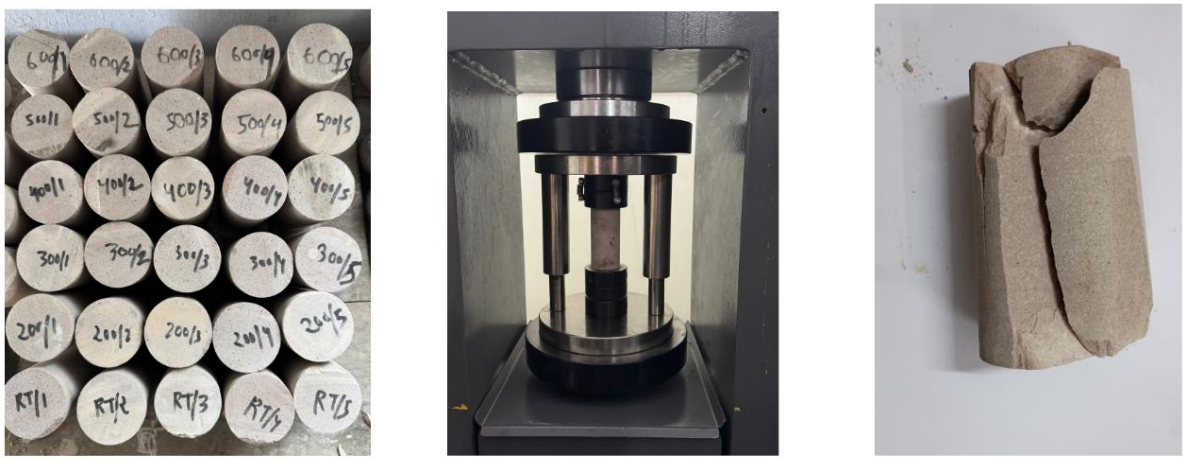


**Figure 3.6** Different steps in UCS determination

## 3.6 Brazilian tensile strength test

The tensile strength of Chunar sandstone was predicted using a BTS test. The strength is expressed in MPa. The test was carried out using an Aimil automatic compression testing machine, having a capacity of 50 kN. It has provisions for automatically adjusting the pump on and off, controlling the set pace rate, and switching the machine off under predetermined conditions. The control releases the pressure at the end of every run and reinitializes the machine at the beginning of every test. The entire system consists of a loading unit, pumping unit, and enhanced digital indicator. The machine can be operated as a standalone with the enhanced digital indicator as well as with Aimil software installed on a desktop PC or laptop. Eighteen samples were subjected to the BTS test; they were prepared in six batches having three samples each. All these batches were subjected to different temperatures ranging from 100–600°C in intervals of 100°C. The samples were inserted into an assembly and then introduced to the machine as shown in figure 3.7. The samples have a length-to-diameter ratio

of 0.5. The values of load applied can be noted and thereafter the BTS values can be computed using the formula:

$$BTS\ (MPa) = 2F/ (3.14 \times D \times T)$$

Where F stands for load(N), D stands for Diameter of Sample (mm), T stands for Thickness of Sample (mm).

**Figure 3.7** Determination of tensile strength of sandstone

## 3.7 Triaxial compression test

This test is used for determining the strength and deformation behaviour of rock under triaxial state condition. The triaxial compression test involves application of load in axial direction on the specimen enclosed in Hoek cell and subjected to confining pressure so as to fail the rock in compression. In laboratory triaxial tests, the intermediate stress $\sigma_2$ is equal to $\sigma_3$ and is lesser than $\sigma_1$. The triaxial test is used for determining mechanical properties of rocks like cohesion and angle of internal friction. The triaxial test was carried out using ADVANTEST 9 ROCK and SERCOMP 7 ROCK instruments. Herein ADVANTEST 9 ROCK offers axial compression and SERCOMP 7 ROCK offers confining pressure onto the sample. The SERCOMP 7 ROCK offers maximum working pressure of 700 bar, maximum oil delivery rate of 0.7 l/min. It had servo-hydraulic control console for confining pressure control into the Hoek cell (triaxial test only). It also has a remotely controlled unit, fully operated by the Advantest rock software. The sample used for the test have length to diameter ratio of 2. 18 samples were considered for study, each subjected to a different scale of temperature,

namely room temperature ( RT) , 200°C, 300°C, 400°C, 500°C,600°C with the increment of 100°C. The samples were subjected to different confining pressures of 5,10,15 MPa. Three samples were considered as a single set each representing a single temperature. There were six sets in all. The triaxial machine is shown in figure 3.8 .

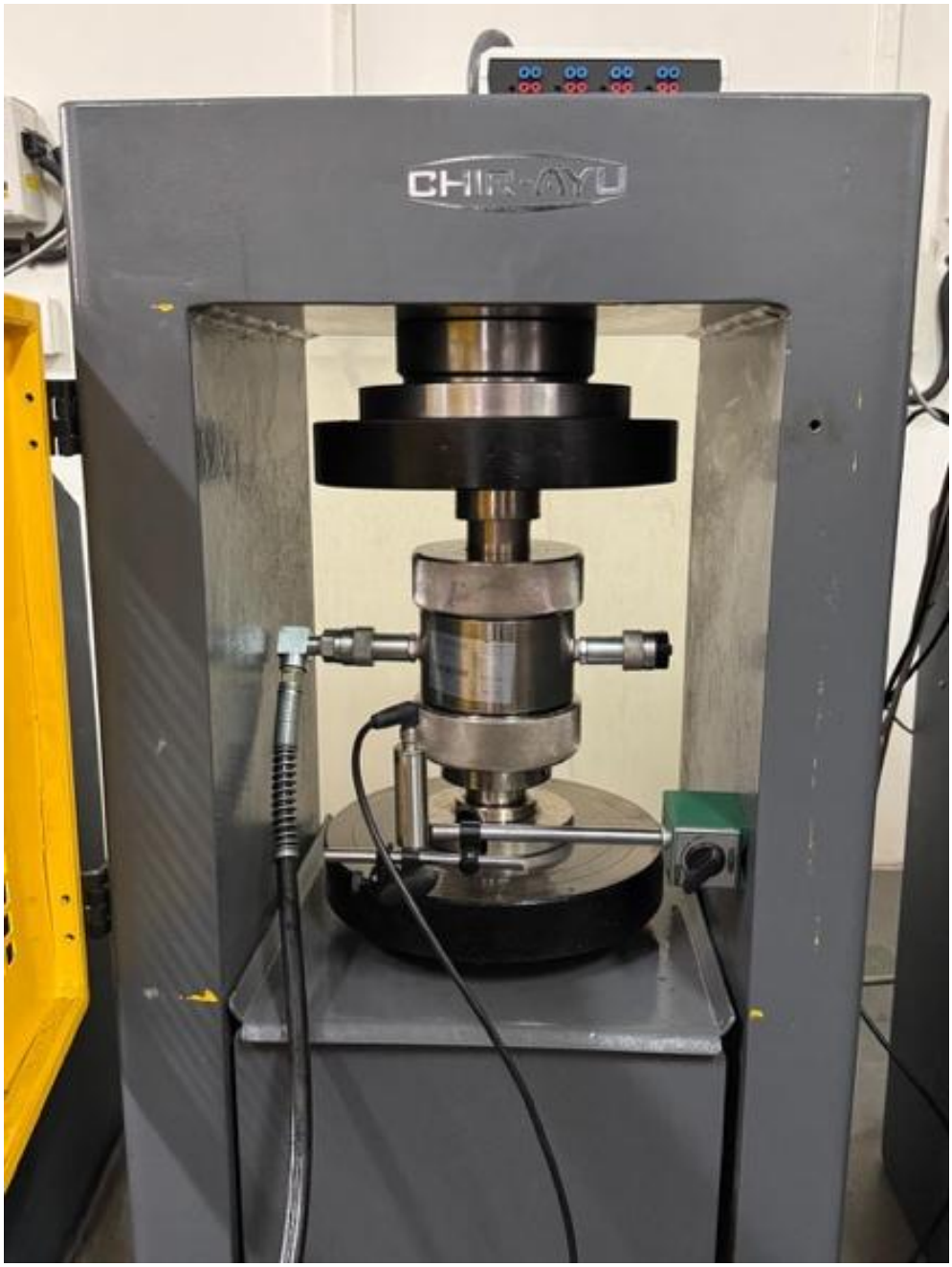



**Figure 3.8** Triaxial machine

## 3.8 X-Ray fluorescence

It is a non-destructive test used for determining the elemental composition of rock. X-rays are emitted from the samples when they are excited by a source of X-rays. These emitted rays are then analysed different elements present in the samples produce characteristic X-rays, which are unique to each specific element. This approach provides important information on the composition of a rock specimen by revealing the existence of major, minor, and trace elements within it. This method allows for a rapid and non-destructive analysis of multiple elements in a variety of materials, including rocks. The technique is widely used to quickly ascertain elemental makeup and identify distinct minerals in fields such as geology, mining, archaeology, environmental research, and related disciplines. The Chunar sandstone samples were subjected to this test in six batches, each representing a different temperature range from 100°C to 600°C. The samples were converted into powdered form and analysed using the SHIMADZU EDX-7000 XRF spectrophotometer as shown in figure 3.9. The machine generated plots of mineral compositions for the sandstone samples. Samples for testing were prepared by producing fine powder of the rock (around 1–2 grams) and introducing it into the machine.

**Figure 3.9** Determining mineralogical composition using XRF test

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 Analysis of x-ray fluorescence test

The XRF data reveals that silica is the major component of sandstone, followed by aluminium oxide and potassium oxide, while other minerals are present in trace amounts as shown in table 4.1. The proportion of silica was found to fluctuate with temperature, with the highest proportion observed at room temperature. Certain minerals like vanadium oxide and silver oxides were detected in trace amounts and categorized under the "others" section. The high silica content imparts strength to the rock. From the perspective of brittleness, minerals like silica contribute to the brittle properties of the rock. The proportions of minerals such as SrO, $Y_2O_3$, and CuO remain nearly constant with temperature, whereas those of $SiO_2$, $Al_2O_3$, and $K_2O$ show slight variations with temperature. The plot generated by test is shown in figure 4.1.

**Table 4.1** Mineralogical composition of sandstone at different temperature

| **SAMPLES** | **RT(25°C)** | **200°C** | **300°C** | **400°C** | **500°C** | **600°C** |
|---|---|---|---|---|---|---|
| **COMPOUNDS** | **MASS %** | | | | | |
| $SiO_2$ | 81.645 | 77.692 | 77.988 | 81.283 | 77.505 | 80.382 |
| $Al_2O_3$ | 16.041 | 19.499 | 19.131 | 16.292 | 19.209 | 16.736 |
| $K_2O$ | 1.542 | 2.010 | 1.913 | 1.680 | 2.142 | 1.709 |
| $Fe_2O_3$ | 0.533 | 0.769 | 0.756 | 0.593 | 0.808 | 0.981 |
| $TiO_2$ | 0.133 | 0.172 | 0.167 | 0.124 | 0.179 | 0.156 |
| $ZrO_2$ | 0.009 | 0.013 | 0.012 | 0.008 | 0.014 | 0.007 |
| MnO | 0.006 | 0.013 | 0.018 | 0.006 | 0.014 | 0.012 |
| $Rb_2O$ | 0.003 | 0.005 | 0.004 | 0.004 | 0.005 | 0.003 |
| SrO | 0.003 | 0.004 | 0.003 | 0.002 | 0.004 | 0.002 |
| CuO | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $Y_2O_3$ | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| others | 0.102 | 0.120 | 0.018 | 0 | 0.118 | 0 |

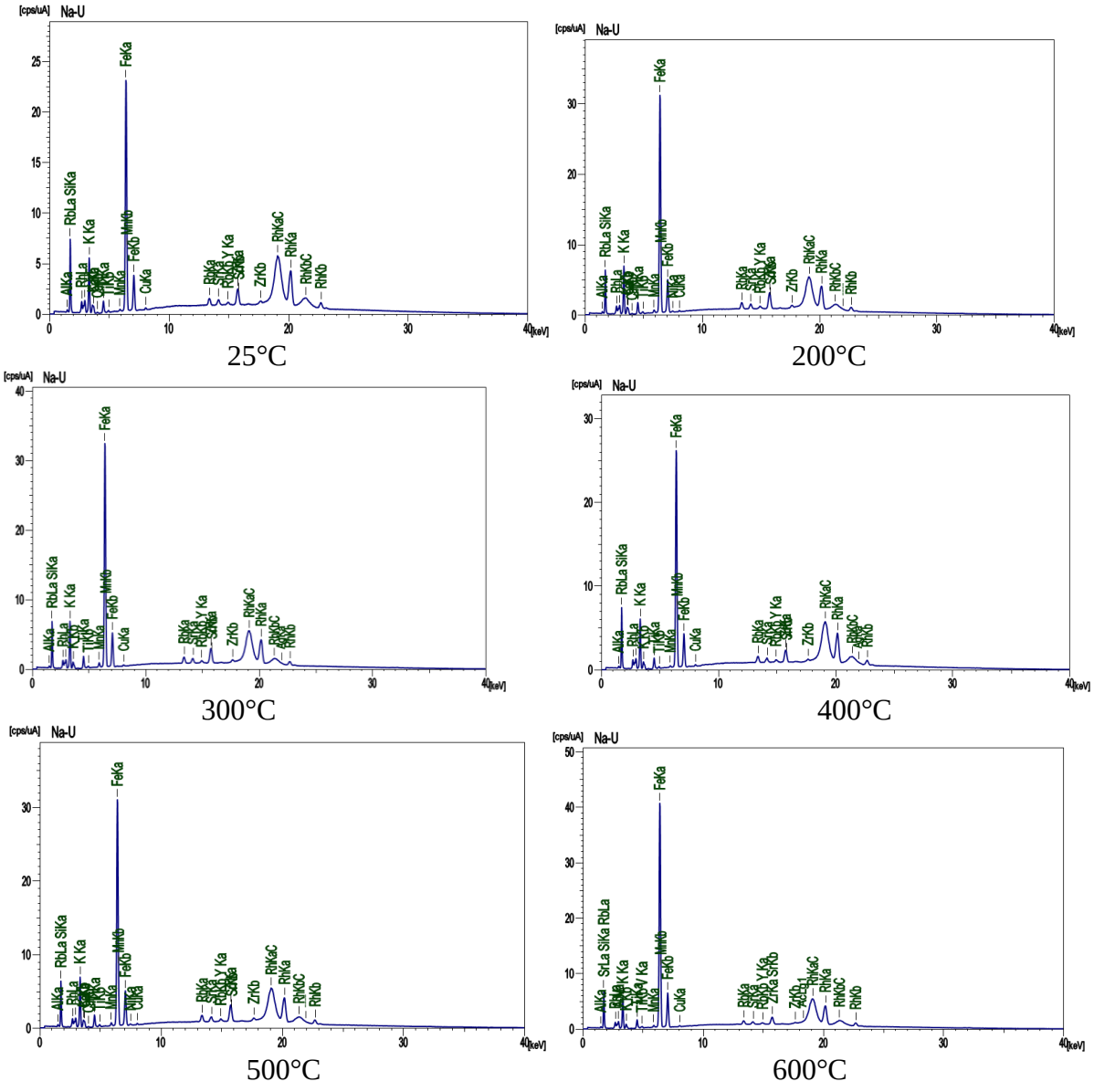



**Figure 4.1** X - ray fluorescence result of Chunar sandstone

## 4.2 Analysis of porosity

Porosity was computed for different samples, earlier the dry weight was computed for all samples, three samples were considered at particular temperature and therefore the set was

prepared. Likewise 6 sets in total were considered here RT means the sample at room temperature. Special assembly was created in order to obtain the submerged weights of samples in water. Thereafter the samples were kept saturated in water for 24 Hrs and weight was taken Thereafter. The value of porosity was found to increase with increase in temperature as shown in table 4.2. Porosity can be defined as volume of void divided by total volume (volume of void+ volume of solids). Now with the rise in temperature, the water trapped within the rock matrix will evaporate as a result the volume of void within the matrix will increase as a result the porosity of sandstone increases. The value of porosity was as low as 6 at room temperature and it goes past 8 at 300°C and thereafter increases by small proportion Till 400°C then again increases till 600°C as shown in figure 4.2. This rise in porosity in a temperature range of 400-600°C is because of development of pores within the matrix. The water present in the pores gets evaporated at high temperatures, generating Voids within the rock matrix, these voids in turn contribute to enhanced porosity of the sandstone.

**Table 4.2** Porosity of Chunar sandstone

| **Sample** | **Dry Weight** | **Submerged Weight** | **Saturated Weights** | **Porosity** |
|---|---|---|---|---|
| RT-1 | 142.29 | 96.70 | 145.11 | 5.82 |
| RT-2 | 135.69 | 93.36 | 138.90 | 7.05 |
| RT-3 | 134.96 | 93.38 | 137.99 | 6.79 |
| 200-1 | 153.76 | 103.60 | 157.82 | 7.49 |
| 200-2 | 151.08 | 101.92 | 154.96 | 7.33 |
| 200-3 | 157.50 | 105.75 | 161.86 | 7.77 |
| 300-1 | 138.20 | 96.75 | 141.93 | 8.26 |
| 300-2 | 142.57 | 98.36 | 146.40 | 7.98 |
| 300-3 | 134.12 | 90.87 | 137.98 | 8.20 |
| 400-1 | 135.17 | 91.01 | 139.39 | 8.72 |
| 400-2 | 135.70 | 91.20 | 139 | 8.71 |
| 400-3 | 145.40 | 99.76 | 149.37 | 8 |
| 500-1 | 133.74 | 93.02 | 137.86 | 9.20 |
| 500-2 | 140.18 | 96.98 | 144.46 | 9.01 |
| 500-3 | 147.43 | 99.57 | 151.63 | 8.06 |
| 600-1 | 144.31 | 95.10 | 149.065 | 8.81 |

| | | | | |
|---|---|---|---|---|
| 600-2 | 156.34 | 103.67 | 162.192 | 10.01 |
| 600-3 | 148.65 | 92.79 | 154.55 | 9.56 |

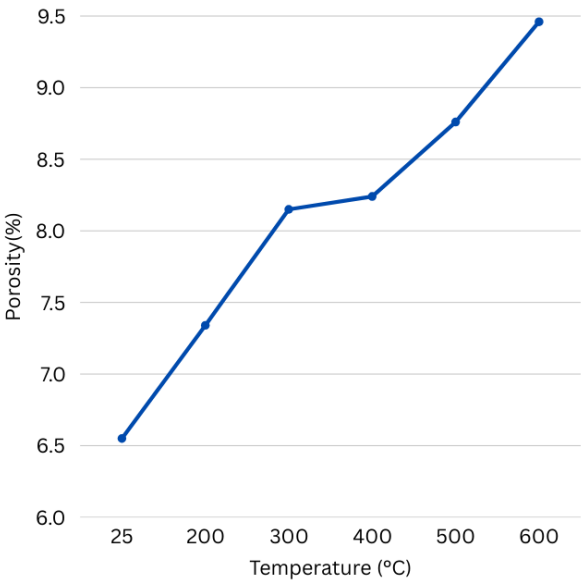



**Figure 4.2** Plot of porosity with temperature

## 4.3 Analysis of Brazilian tensile strength and density

The values of Brazilian tensile strength were initially found to increase with temperature till 400°C and thereafter decrease till 600°C. The initial values was 6.02 MPa at room temperature and thereafter increases to 8.50MPa at 400°C which was the maximum value and thereafter again decreased to 6.35 MPa at 600°C as shown in table 4.3. The fall in strength, post 400°C matches with that of Gang et al. (2007). The change in microstructure of sandstone along with thermal stress were reason for the deterioration of mechanical properties as per Gang et al. (2007) at temperature range of 400-600°C development of pores within the matrix occurs which cause reduction in strength of sandstone. Relationship between tensile strength and temperature is shown in figure 4.3.

**Table 4.3** Brazilian tensile strength of Chunar sandstone

| Sample | Length | Diameter | Load (KN) | BTS | Overall |
|---|---|---|---|---|---|
| RT1 | 26.96 | 54.68 | 10.2 | 4.41 | |
| RT2 | 27.77 | 53.64 | 13.4 | 5.73 | 6.02 |
| RT3 | 27.52 | 54.86 | 18.78 | 7.92 | |
| 200-1 | 27.24 | 53.38 | 15.36 | 6.73 | |
| 200-2 | 25.54 | 53.48 | 13.98 | 6.52 | 6.99 |
| 200-3 | 26.33 | 54.16 | 17.34 | 7.74 | |
| 300-1 | 25.04 | 53.43 | 17.42 | 8.28 | |
| 300-2 | 23.67 | 53.48 | 18.78 | 9.35 | 7.66 |
| 300-3 | 25.49 | 53.39 | 21.62 | 11.36 | |
| 400-1 | 25.97 | 53.50 | 18.12 | 8.30 | |
| 400-2 | 26.07 | 53.77 | 19.18 | 8.71 | 8.50 |
| 400-3 | 25.73 | 53.75 | 18.44 | 8.49 | |
| 500-1 | 24.81 | 53.44 | 17.32 | 8.32 | |
| 500-2 | 25.87 | 53.60 | 13.12 | 6.02 | 7.33 |
| 500-3 | 28.02 | 53.65 | 18.08 | 7.66 | |
| 600-1 | 28.19 | 53.25 | 14.68 | 6.23 | |
| 600-2 | 27.99 | 53.08 | 16.92 | 6.99 | 6.35 |
| 600-3 | 28.78 | 53.67 | 14.14 | 5.83 | |

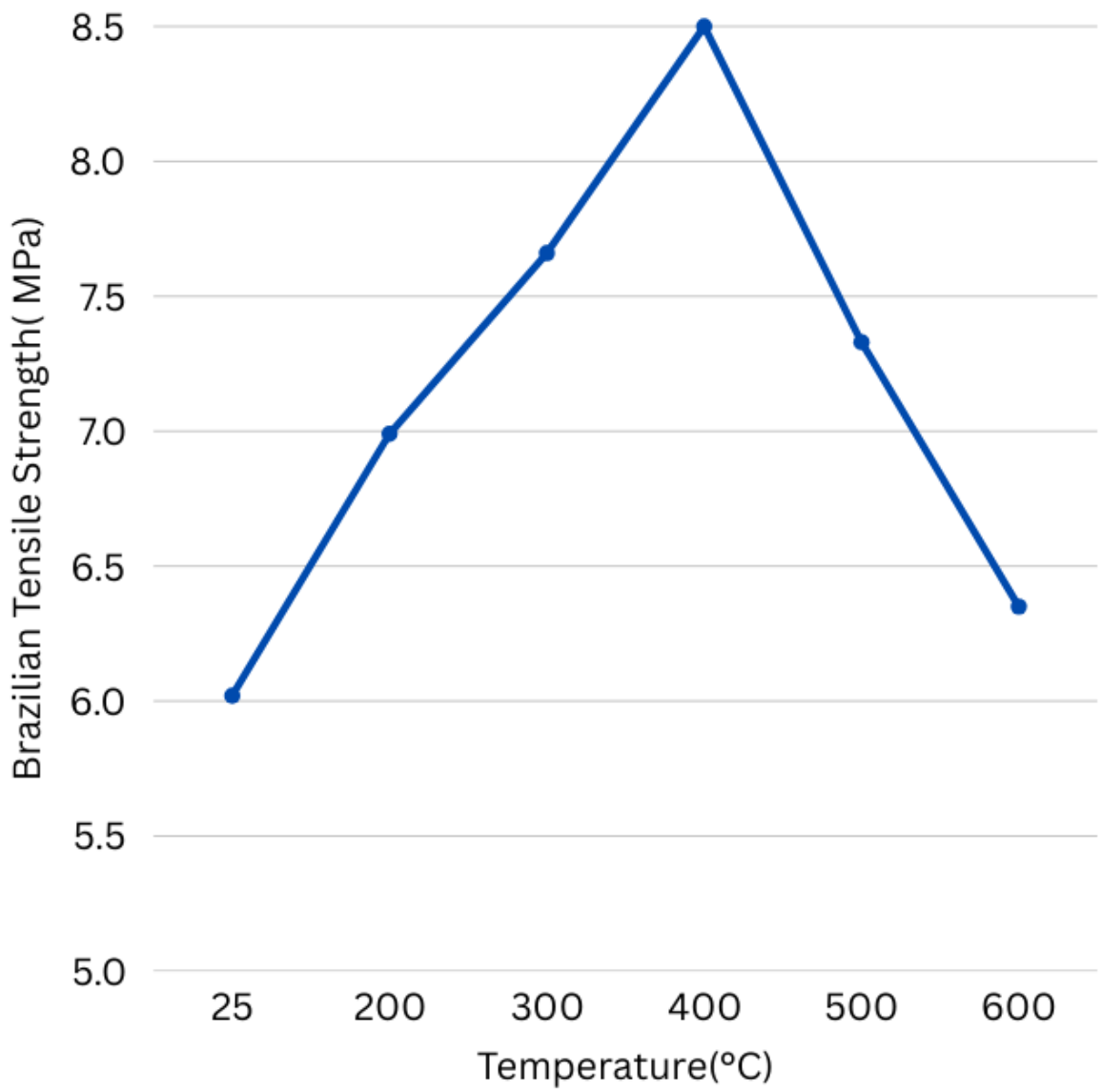



**Figure 4.3** Plot of Brazilian tensile strength with temperature

The density was found to decrease with increase in temperature. The maximum value of density was at room temperature which was around 2446 Kg/m3 and minimum value was obtained at 600°C which was 2353 Kg/m3 as per table 4.3 .This trend in density matches that of Singh et al. (2023). The fall in density can be related to increase in volume which is evident from the plot of porosity as per which the volume of void was increasing with temperature. Therefore the volume increases and density decreases. For 200-300°C the density remained nearly constant, that means that the volume change in that region is not significant, mainly because the generated voids gets filled up material with matrix therefore despite the generation of microcracks the volume change is not significant. The plot of variations in density against temperature is shown in figure 4.4

**Table 4.4** Measurements of dimensions and density of samples

| Sample | $L_1$ | $L_2$ | $L_3$ | $L_{avg}$ | $D_1$ | $D_2$ | $D_3$ | $D_{avg}$ | Weight | Volume | Density |
|---|---|---|---|---|---|---|---|---|---|---|---|
| U-RT | 109.33 | 109.41 | 109.42 | 109.39 | 54.90 | 55.05 | 54.58 | 54.84 | 636 | 258405.62 | 2461.25 |
| T-RT-1 | 107.05 | 106.60 | 106.58 | 106.74 | 53.13 | 53.55 | 53.83 | 53.50 | 569 | 239989.54 | 2370.94 |
| T-RT-2 | 110.39 | 109.97 | 110.34 | 110.23 | 55.78 | 55.30 | 54.81 | 55.30 | 638 | 264728.52 | 2410.02 |
| T-RT-3 | 110.25 | 110.24 | 110.08 | 110.19 | 52.69 | 53.53 | 52.08 | 52.77 | 604 | 240963.57 | 2506.60 |
| U-200 | 112.30 | 112.15 | 111.75 | 112.07 | 53.48 | 53.37 | 53.53 | 53.46 | 596 | 2369.31 | 2369.31 |
| T-200-1 | 107.16 | 106.95 | 106.67 | 106.93 | 55.03 | 54.92 | 53.92 | 54.62 | 619 | 2470.35 | 2470.35 |
| T-200-2 | 111.14 | 111.16 | 111.65 | 111.32 | 54.83 | 54.82 | 54.93 | 54.86 | 640 | 2432.31 | 2432.31 |
| T-200-3 | 108.62 | 108.75 | 108.54 | 108.64 | 54.85 | 54.83 | 54.84 | 54.84 | 625 | 2435.67 | 2435.67 |
| U-300 | 109.40 | 109.33 | 109.54 | 109.42 | 53.49 | 53.34 | 53.51 | 53.45 | 602 | 245503.29 | 2243.61 |
| T-300-1 | 112.70 | 112.78 | 112.69 | 112.72 | 54.79 | 55.36 | 54.63 | 54.93 | 649 | 267097.73 | 2369.50 |
| T-300-2 | 109.43 | 109.32 | 109.75 | 109.50 | 53.38 | 54.10 | 53.41 | 53.63 | 601 | 247354.37 | 2258.94 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T-300-3 | 109.06 | 108.99 | 108.78 | 108.94 | 54.79 | 54.99 | 55.04 | 54.94 | 629 | 258266.37 | 2370.65 |
| U-400 | 110.49 | 110.45 | 110.60 | 110.51 | 53.33 | 53.47 | 53.42 | 53.41 | 607 | 247568.57 | 2451.85 |
| T-400-1 | 109.82 | 109.74 | 109.96 | 109.84 | 54.04 | 53.48 | 53.49 | 53.67 | 580 | 248492.68 | 2334.07 |
| T-400-2 | 111.18 | 110.71 | 110.72 | 110.87 | 54.85 | 54.81 | 54.98 | 54.88 | 639 | 262260.05 | 2436.51 |
| T-400-3 | 108.10 | 108.38 | 108.39 | 108.28 | 53.48 | 53.62 | 53.06 | 53.39 | 571 | 242383.88 | 2255.77 |
| UCS-500 | 109.20 | 108.58 | 108.64 | 108.81 | 54.50 | 53.68 | 53.64 | 53.94 | 589 | 248637.87 | 2368.91 |
| T-500-1 | 113.60 | 114.11 | 113.55 | 113.75 | 55.25 | 55.21 | 55.02 | 55.16 | 654 | 247833.22 | 2405.89 |
| T-500-2 | 114.67 | 114.89 | 114.54 | 114.70 | 56.40 | 55.23 | 54.93 | 55.52 | 660 | 277684.57 | 2376.79 |
| T-500-3 | 112.56 | 112.69 | 112.34 | 112.53 | 54.80 | 53.96 | 53.58 | 54.11 | 622 | 262960.67 | 2365.67 |
| UCS-600 | 109.58 | 109.19 | 109.10 | 109.29 | 55.36 | 55.66 | 55.76 | 55.59 | 623 | 265286.86 | 2348.40 |
| T-660-1 | 110.75 | 110.85 | 110.53 | 110.71 | 55.06 | 55.19 | 55.09 | 55.11 | 633 | 264113.19 | 2396.70 |
| T-600-2 | 109.83 | 109.86 | 109.68 | 109.79 | 53.27 | 53.66 | 53.99 | 53.64 | 608 | 248101.97 | 2450.61 |
| T-600-3 | 108.67 | 108.33 | 108.36 | 108.45 | 53.56 | 53.96 | 53.64 | 53.72 | 584 | 245812.97 | 2375.79 |

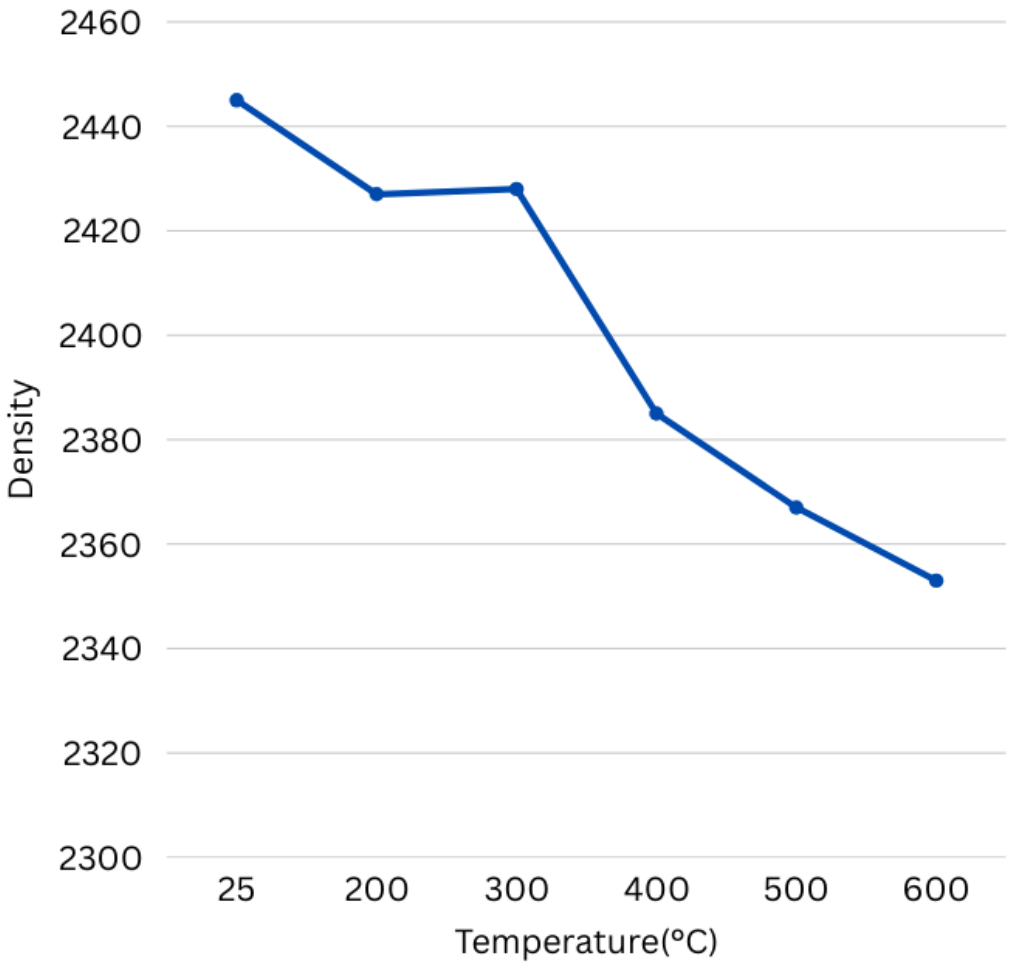



**Figure 4.4** Variations of density with temperature

**Table 4.5** Variations of Vp and Vs with temperature

| **Sample** | **Vp** | | **VS** | |
|---|---|---|---|---|
| U-RT | 3243 | 3479.75 | 2535 | 2602 |
| T-RT-1 | 4202 | | 3008 | |
| T-RT-2 | 3149 | | 2460 | |
| T-RT-3 | 3145 | | 2405 | |
| U-200 | 3871 | | 2813 | |

| | | | | |
|---|---|---|---|---|
| T-200-1 | 3253 | 3399.25 | 2471 | 2559.75 |
| T-200-2 | 3140 | | 2365 | |
| T-200-3 | 3283 | | 2590 | |
| U-300 | 3149 | 3143.5 | 2313. | 2404 |
| T-300-1 | 3051 | | 2209 | |
| T-300-2 | 3224 | | 2571 | |
| T-300-3 | 3149. | | 2523 | |
| U-400 | 2850 | 2923 | 2488 | 2276.5 |
| T-400-1 | 2813 | | 2061 | |
| T-400-2 | 2970 | | 2323 | |
| T-400-3 | 3059 | | 2234 | |
| U-500 | 2769 | | 2077 | |
| T-500-1 | 2500 | | 1878 | |
| T-500-2 | 2547 | 2590 | 1964 | 1929 |
| T-500-3 | 2455 | | 1798 | |
| U-600 | 2255 | 2224.4 | 1667 | 1761.5 |
| T-600-1 | 2275 | | 1776 | |
| T-600-2 | 2030 | | 1818 | |
| T-600-3 | 2338 | | 1785 | |

The waves velocity was found to decrease with temperature as shown in figure 4.5 .The result is in accordance with the findings of Singh et al. (2023). The reason for the same was the rise in pores within the rock matrix with rise in temperature, we knew that porosity was found to

increase with increase in temperature and that means that the pores spaces in the sandstone sample were increasing with the temperature. Therefore this increase in pores spaces affects the transmission of signals through the sample. Also because of thermal stresses microcracks can develop within the rock matrix, these cracks lowers down the waves transmission in turn lowering down the velocity. The fall in Vp and Vs for temperature of 400°C-600°C indicates that development pores within the rock matrix which eventually causes reduction in waves velocity. Table 4.5 shows how Vp and Vs values changes with temperature.

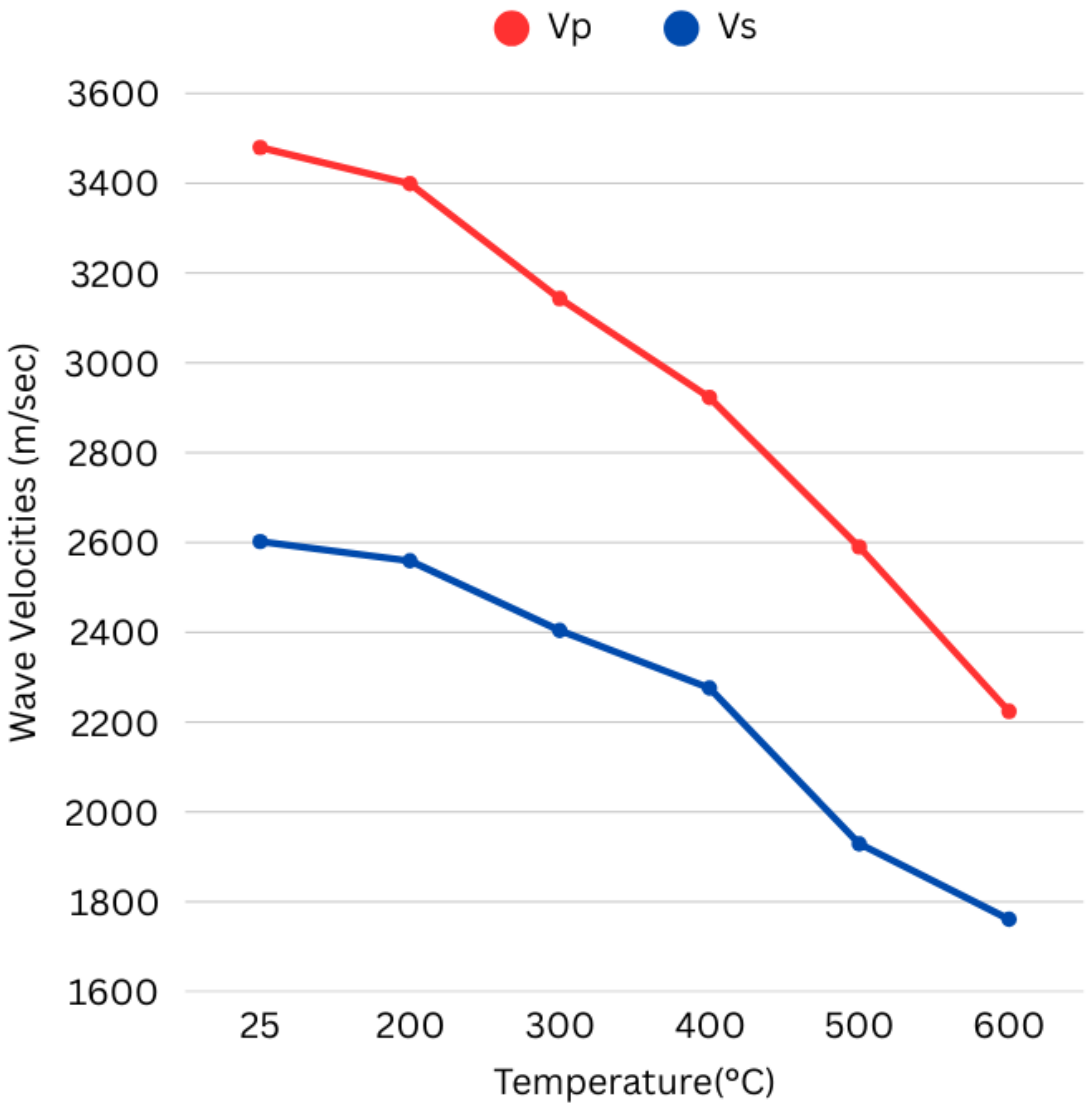



**Figure 4.5** Plot of variations of Vp and Vs with temperature

## 4.4 Analysis of UCS and triaxial tests

**Table 4.6** Result of UCS and triaxial tests

| Temperature (°C) | UCS (MPa) | Triaxial Compressive Strength | | | Cohesion (MPa) | Angle of internal Friction (Φ ) |
|---|---|---|---|---|---|---|
| | | 5 MPa | 10 MPa | 15 MPa | | |
| RT | 67.61 | 130.92 | 152.27 | 194.77 | 13.06 | 51.52° |
| 200 | 112.71 | 142.58 | 154.65 | 176.03 | 28.61 | 37.40° |
| 300 | 88.68 | 165.36 | 179.6 | 225.74 | 16.61 | 52.79° |
| 400 | 88.30 | 150.08 | 203.95 | 222.36 | 15.66 | 53.85° |
| 500 | 85.39 | 157.59 | 203.63 | 235.86 | 14.90 | 55.09° |
| 600 | 81.98 | 187. 04 | 220.18 | 232.87 | 15.50 | 55.86° |

Triaxial test results offers the value of major and minor principal stresses, these are used for plotting the Mohr circles and computing the Values of cohesion and angle of internal friction with help of failure envelope. The Blue circle here represents Mohr circle which actually represents state of stress at specific point and is made use of in predicting failure of material, as shown in figure 4.7 .The first circle in the plot represents UCS of sandstone samples at specified temperature and progressive circles are based on triaxial results for 5, 10 and 15 MPa confinement pressure. The red colour spots represents principal stresses and blue coloured points represents tangential points where the failure envelope is tangential to Mohr circles and red dotted Line represents the Mohr coulomb failure envelope. We can observe that the centre of circle represents the mean value of principal stresses and radius represents the average of differences in the principal stresses. The failure envelope represents all those points having a specific combination of normal and shear Stresses required for material failure. The x axis of the plot represents normal stress and the Y axis represents shear stresses. The intercept Of Mohr coulomb failure envelope represents cohesion or rock whereas The slope represents angle of internal friction. Consider Sample at room temperature (25°C) represented By RT the value of UCS was 67.61MPa and since no confinement pressure is applied the confinement pressure

is zero. Therefore one end of the circle is at zero. The other circles represent state of stress at 5MPa, 10MPa and 15 MPa confinement pressure. The failure envelope was developed to obtain the value of cohesion and angle of internal friction. The value of cohesion was 13.06 MPa and that of angle of internal friction was 51.52°C. When temperature was 200°C and nearly 70% rise in UCS was observed , this is in accordance with the result obtained by Jin et al. (2024). The cohesion value rose by nearly 100% and we know as cohesion increases, the angle of internal friction decreases, here by 37.8%.When temperature rose to 300°C ,the value of UCS fell by 21%, this fall in UCS value post peak value matches with observation made by of Jin et al. (2024). Singh et al. (2023) stated that The value of UCS increased till 200°C and thereafter decreased as shown in Figure 4.6, the water loss and structural damage caused by thermal stress were the reason. The value of triaxial strength of rock at 300°C and 400°C was nearly the same, The same was the case with UCS as well. The reason for the same was explained by Ding et al. (2022) Wherein the ablation of rock particles within the matrix and thermal expansion were jointly responsible for this behaviour. The cohesion falls by 6% and angle of internal friction increased by nearly the same proportion For temperature of 500°C and 600°C , The value of UCS gradually decrease this is because of development of pores within the matrix, the water which was there gets evaporated as a result application of uniaxial load causes failure of rock at lower UCS values, but when confinement is provided by confining pressure these pores gets compacted as a result higher amount of load can be taken which is reflected in triaxial results. The rise in angle of internal friction increases meaning the resistance to sliding has increased mainly because of interlocking of particles. The cohesion follows an obvious inverse relationship with angle of internal friction. The resulting samples after triaxial tests are shown in figure 4.8 .

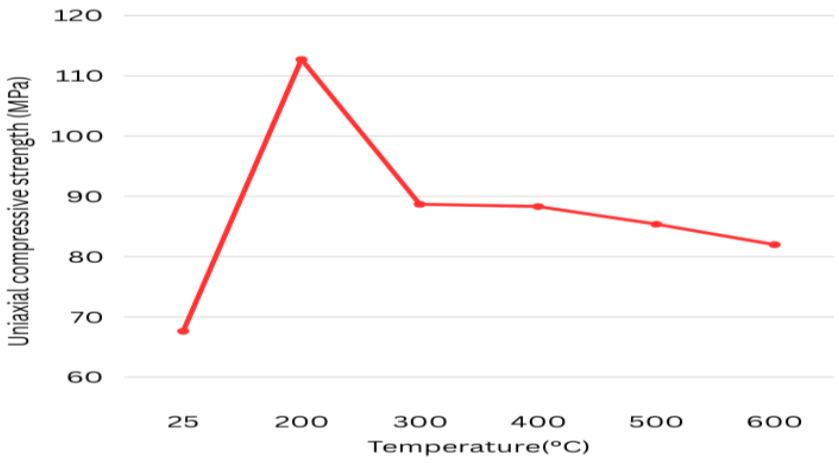
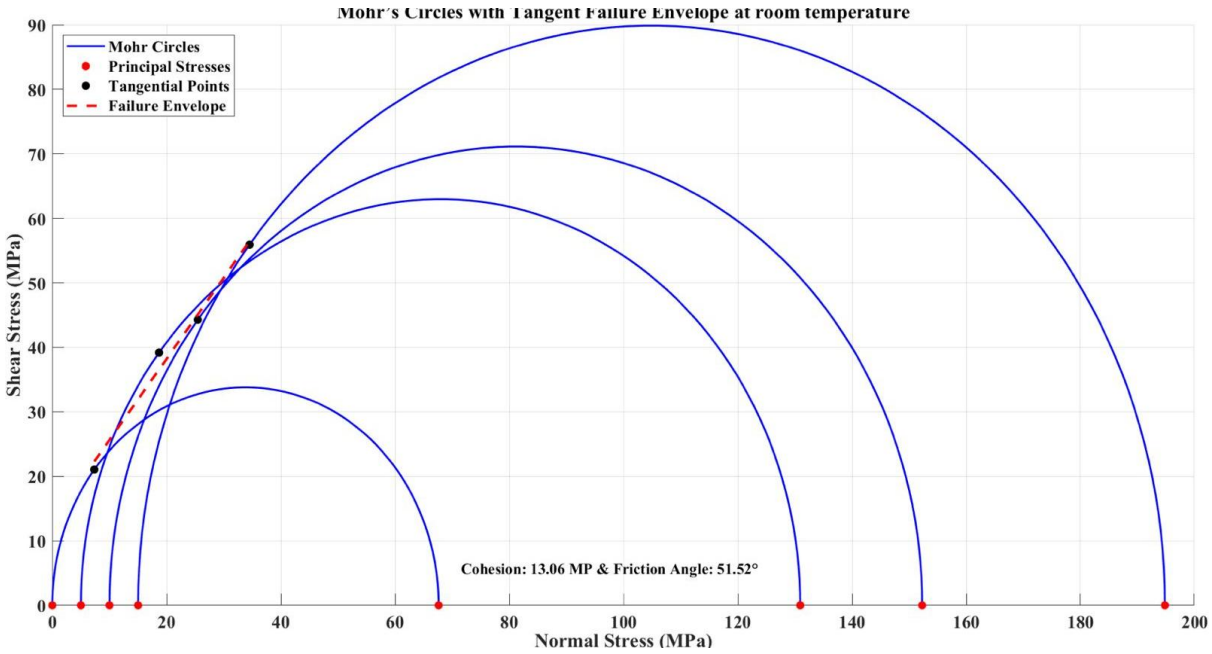
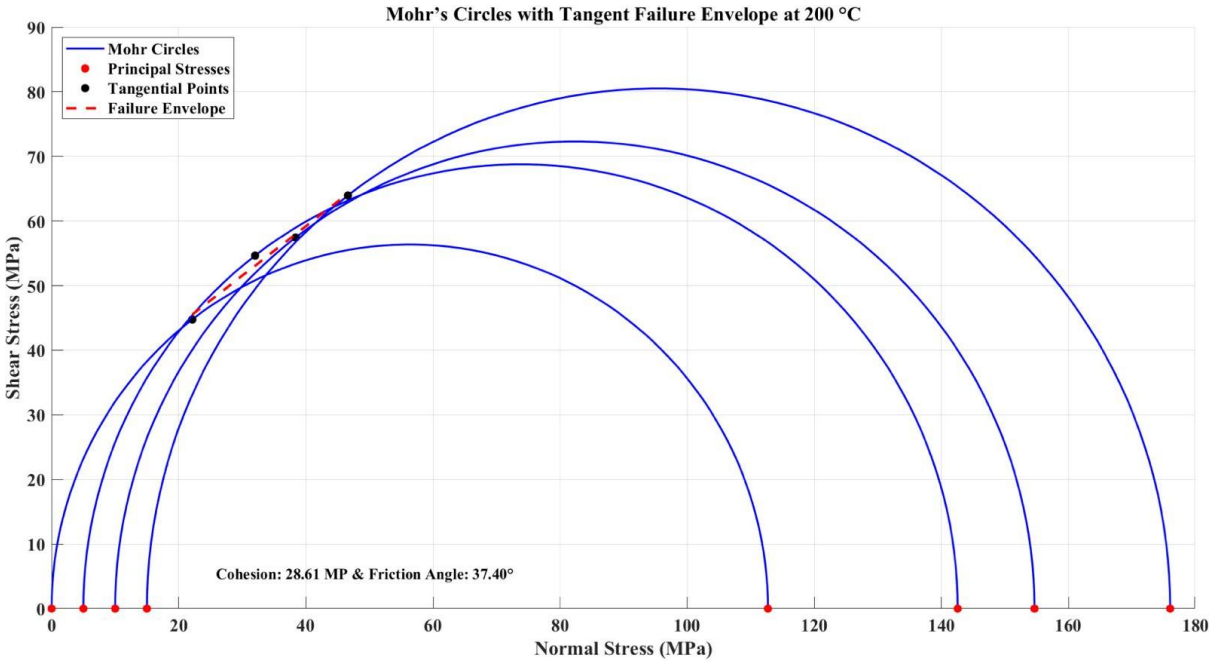


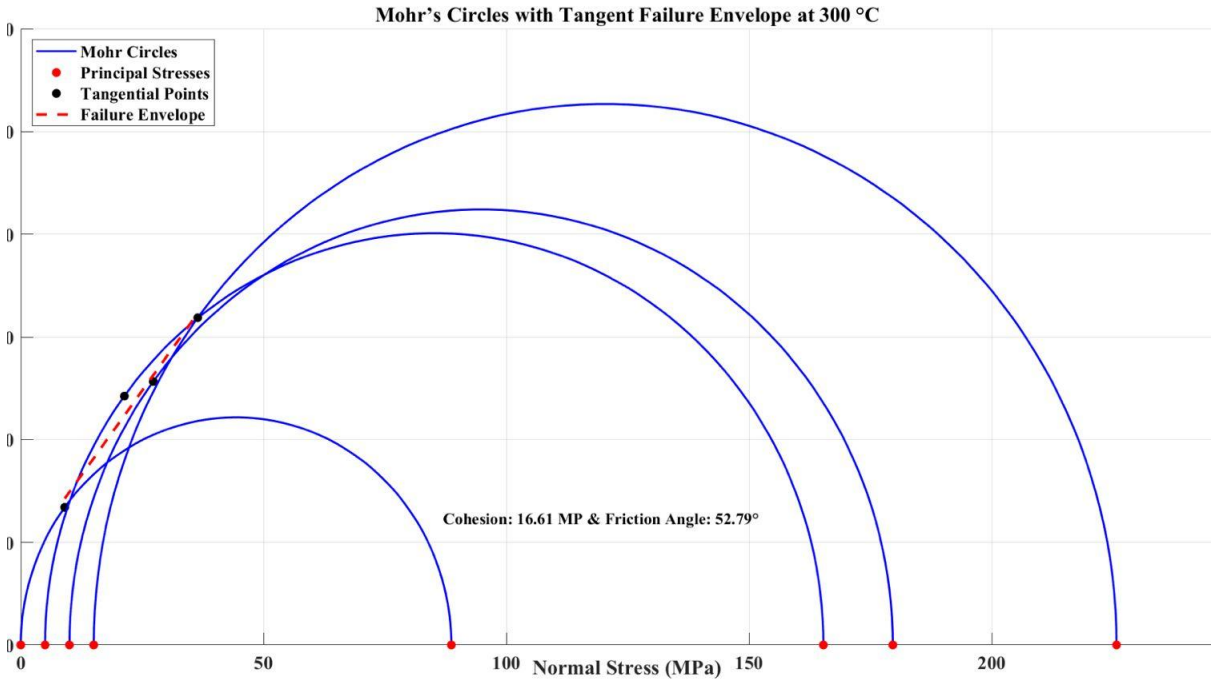

**Figure 4.6** Variation of UCS with temperature


Mohr's Circles with Tangent Failure Envelope at room temperature
Mohr Circles
Principal Stresses
Tangential Points
Failure Envelope
Cohesion: 13.06 MP & Friction Angle: 51.52°
Shear Stress (MPa)
Normal Stress (MPa)

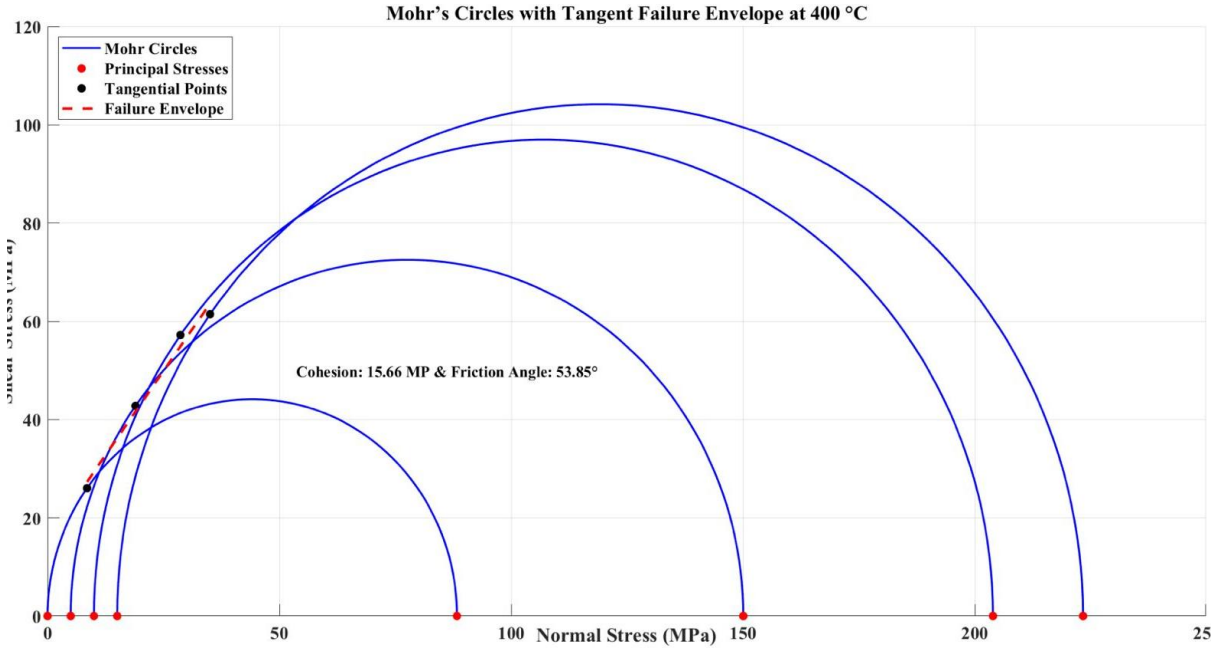
a) 25°C


Mohr's Circles with Tangent Failure Envelope at 200 °C
Mohr Circles
Principal Stresses
Tangential Points
Failure Envelope
Cohesion: 28.61 MP & Friction Angle: 37.40°
Shear Stress (MPa)
Normal Stress (MPa)

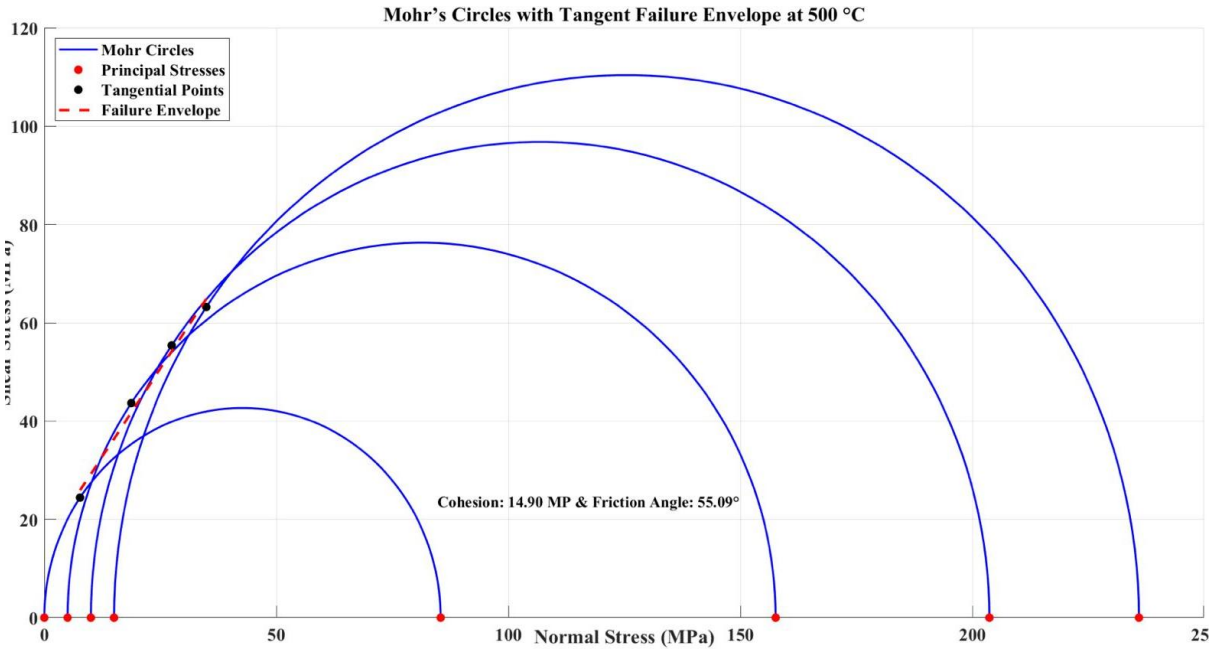
b) 200°C


Mohr's Circles with Tangent Failure Envelope at 300 °C
Mohr Circles
Principal Stresses
Tangential Points
Failure Envelope
Cohesion: 16.61 MP & Friction Angle: 52.79°
0
50
100
150
200
Normal Stress (MPa)

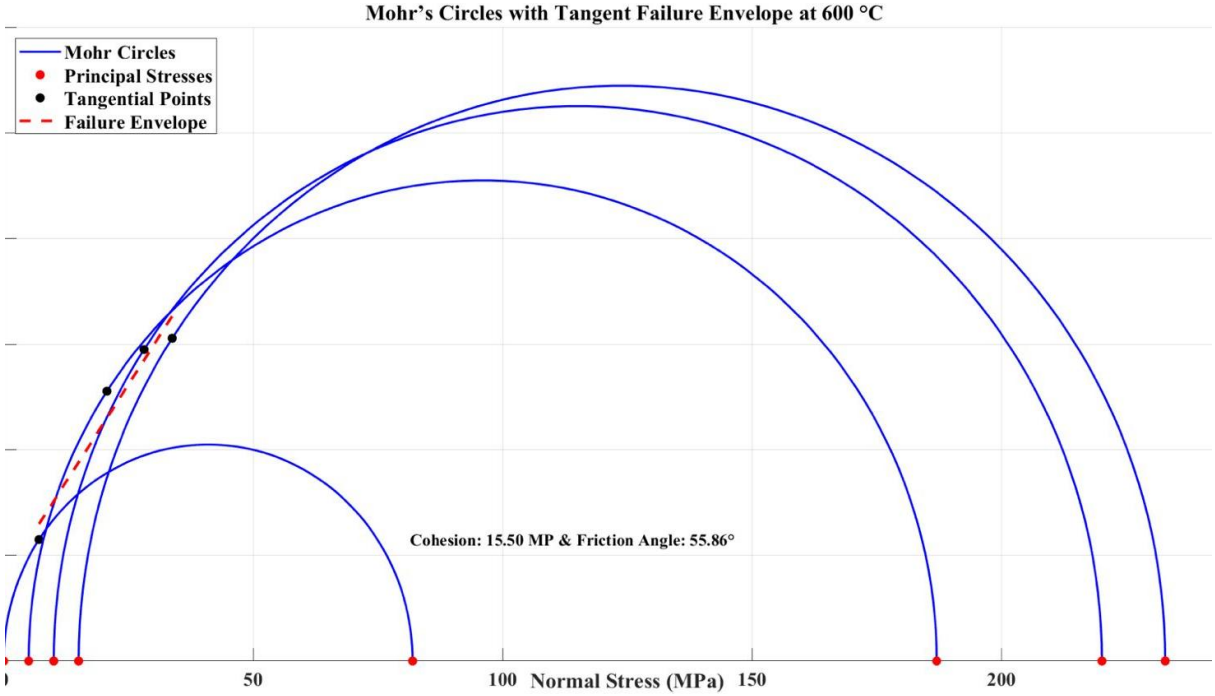
c) 300°C


Mohr's Circles with Tangent Failure Envelope at 400 °C
Mohr Circles
Principal Stresses
Tangential Points
Failure Envelope
Cohesion: 15.66 MP & Friction Angle: 53.85°
120
100
80
60
40
20
0
0
50
100
150
200
25
Normal Stress (MPa)

d) 400°C




e) 500 °C




f) 600 °C

**Figure 4.7** Mohr circles for samples at different level temperatures

a) Room Temperature 25°C.

b) 200°C

c) 300°C.

d) 400°C

e) 500°C.

f) 600°C

**Figure 4.8** Result of triaxial test of samples at different temperatures

## 4.5 Variations of shear strength parameters with temperature

Temperature exerts influence on cohesion and angle of internal friction of sandstone. The plot shown in figure 4.9 represents the relationship between cohesion and angle of internal friction with temperature. The cohesion displayed an inverse relationship with angle of internal friction, this is similar to that observed by Jin et al. (2024). The cohesion value peaked at 200°C , The UCS values also reached its peak at 200°C, this means that at 200°C the particles were closely bonded to one another offering maximum resistance to applied load. Thereafter with rise in temperature the cohesion value decrease and angle of internal Friction increases. As per Jin et al. (2024) The value of angle of internal friction was highest at 600°C In the temperature range of 400-600°C the the development of void spaces occurs in rock matrix because of evaporation of water, This causes internal dehydration of samples, lowering down the moisture content within causing deterioration of mechanical properties in that range , this can be supported by Singh et al. (2023)

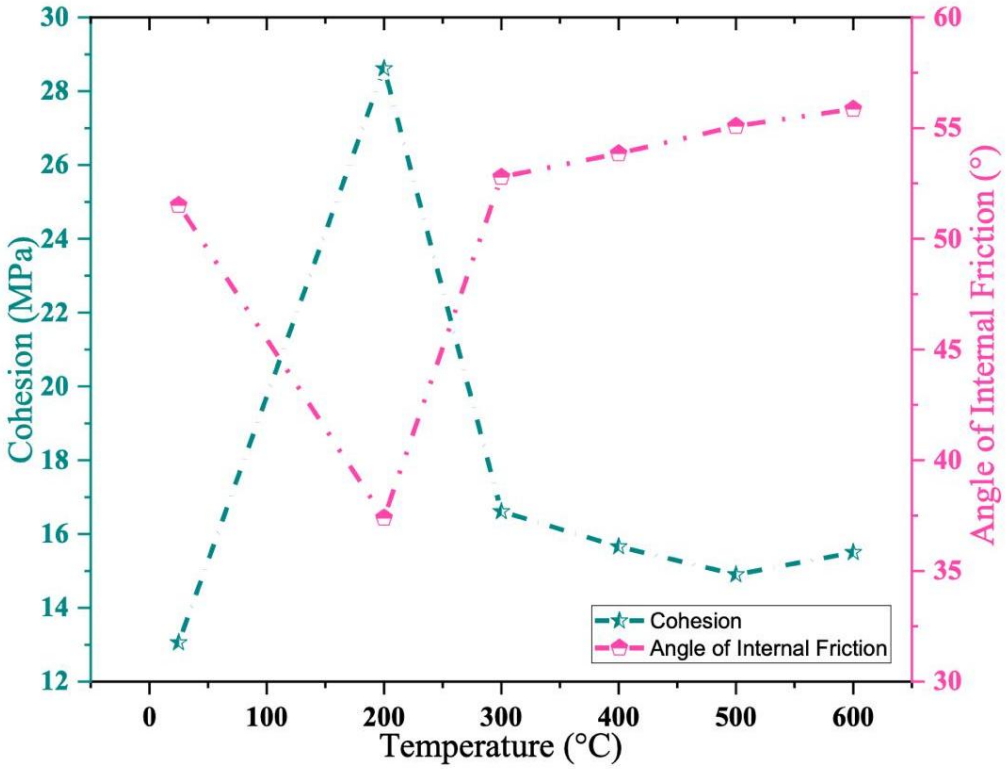



**Figure 4.9** Variations of shear strength parameters with temperature

## 4.6 Determination of brittleness index based on shear strength parameters

After computing various mechanical properties and computing brittleness using strength based brittleness indices. An attempt was made to develop a brittleness index based solely on cohesion and angle of internal friction and study the variation of this index with temperature.

**Brittleness Index=** $\frac{C*(1-\sin\varphi)}{(1+\sin\varphi)}$

Where C is cohesion and $(\varphi)$ is angle of internal friction.

The data was arranged in Ms-Excel thereafter exponential regression analysis was carried out and correlation was determined in between parameters. The following index was proposed based on correlations carried out between the index and other brittleness indices and UCS, cohesion and angle of internal friction. The brittleness index proposed was found to have good correlations with brittleness index $B_1$ as shown in figure 4.10. The value of $R^2$ was found to be 0.91. The value of $R^2$ greater than 0.7 indicates strong model fit indicating that model captures data variability. Figure 4.10 shows the relationship between proposed brittleness index and Brittleness index $B_1$, the result of exponential regression computed value of $R^2$ as 0.91. Similar plots were generated for brittleness index $B_2$ as shown in figure 4.11 and $B_3$, $B_4$ as shown in figure 4.12 and 4.13. However, the correlation with brittleness index $B_4$ was not high enough. Figure 4.14 shows the relationship between proposed brittleness index and UCS, the plot suggests that good correlation was obtained with value of $R^2$ as 0.92.The proposed brittleness index shows good correlation with cohesion and angle of internal friction as well the results of exponential regression reveals that value of $R^2$ was 0.99 and 0.99 respectively for them.

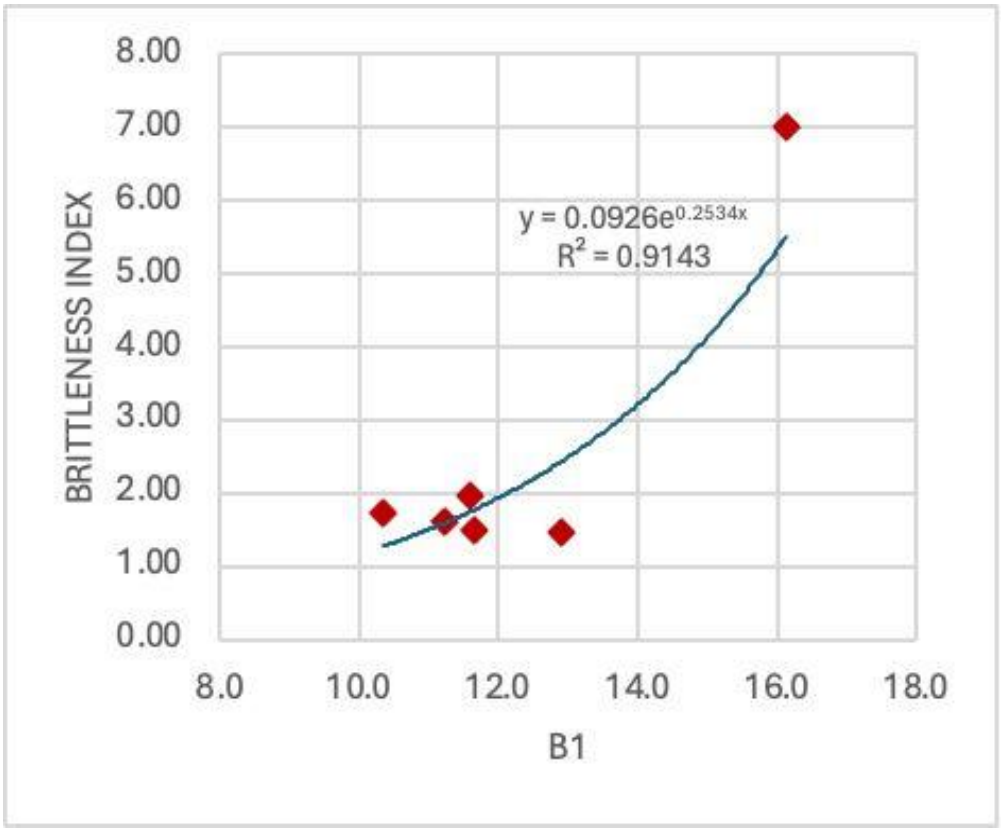



**Figure 4.10** Relationship between proposed brittleness index and $B_1$

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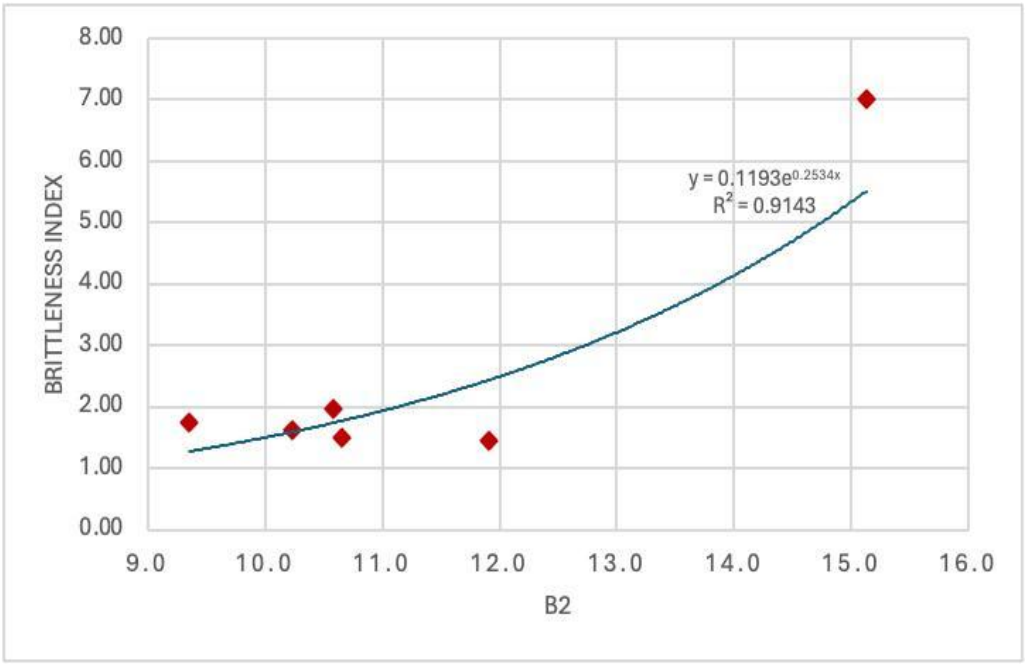


**Figure 4.11** Relationship between proposed brittleness index and $B_2$

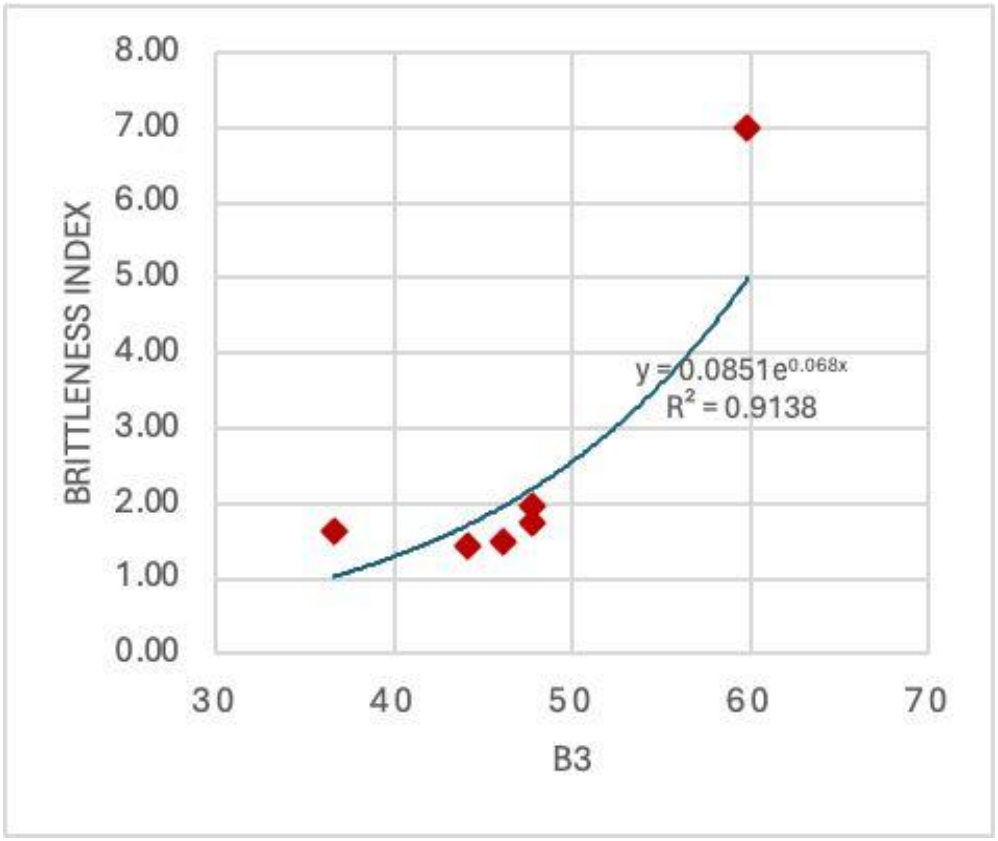


**Figure 4.12** Relationship between proposed brittleness index and $B_3$

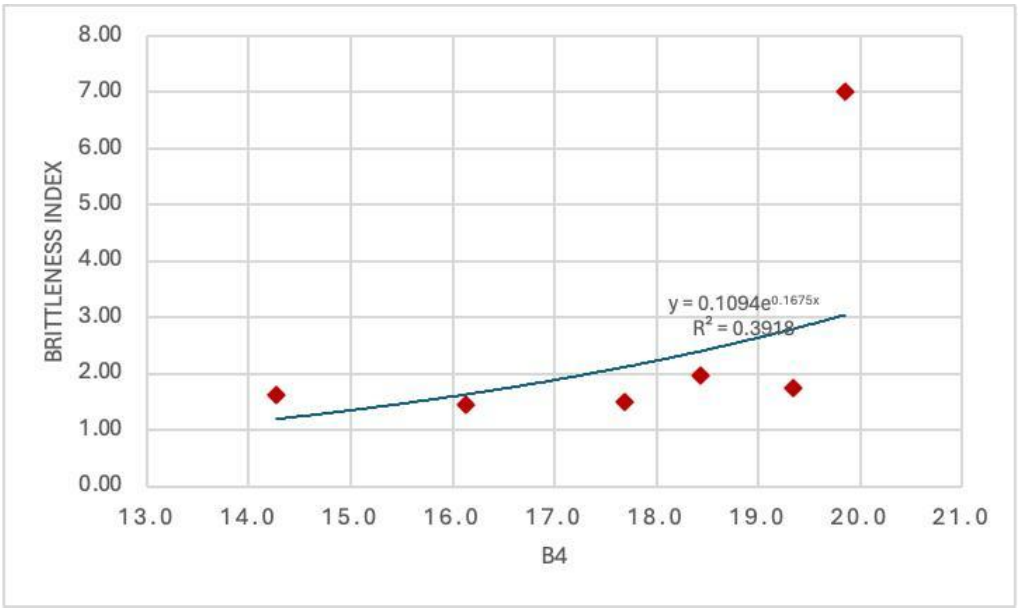


**Figure 4.13** Relationship between proposed brittleness index and $B_4$

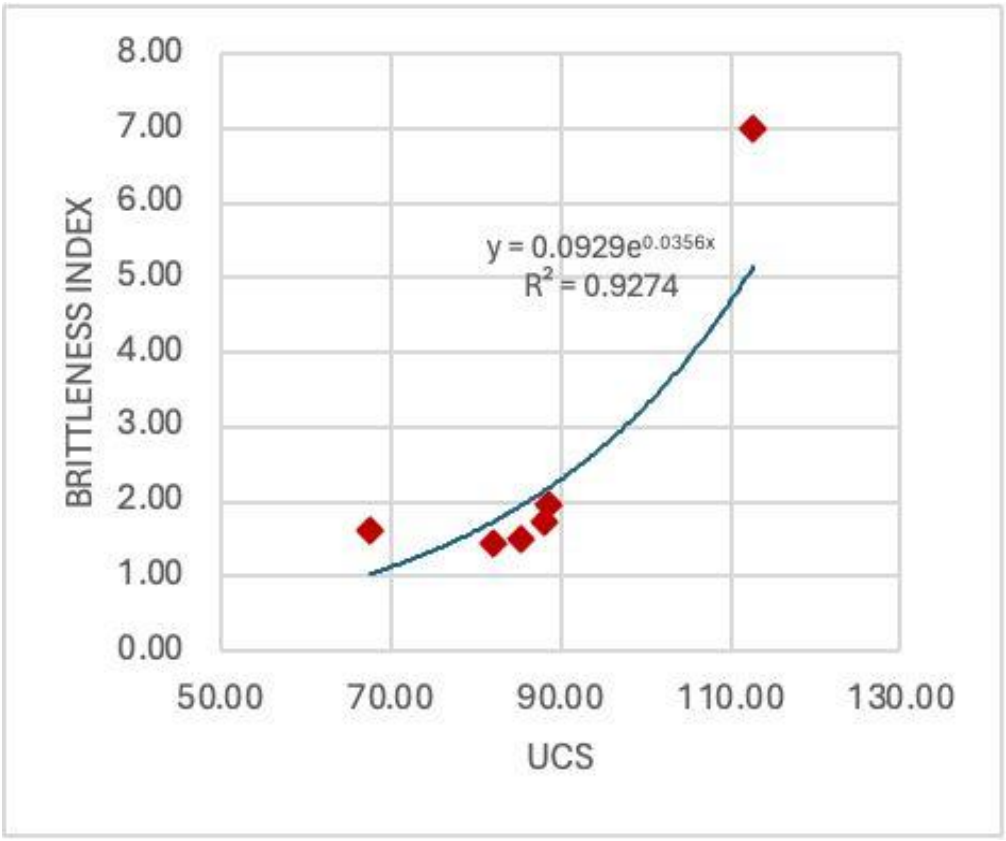


**Figure 4.14** Relationship between proposed brittleness index and UCS

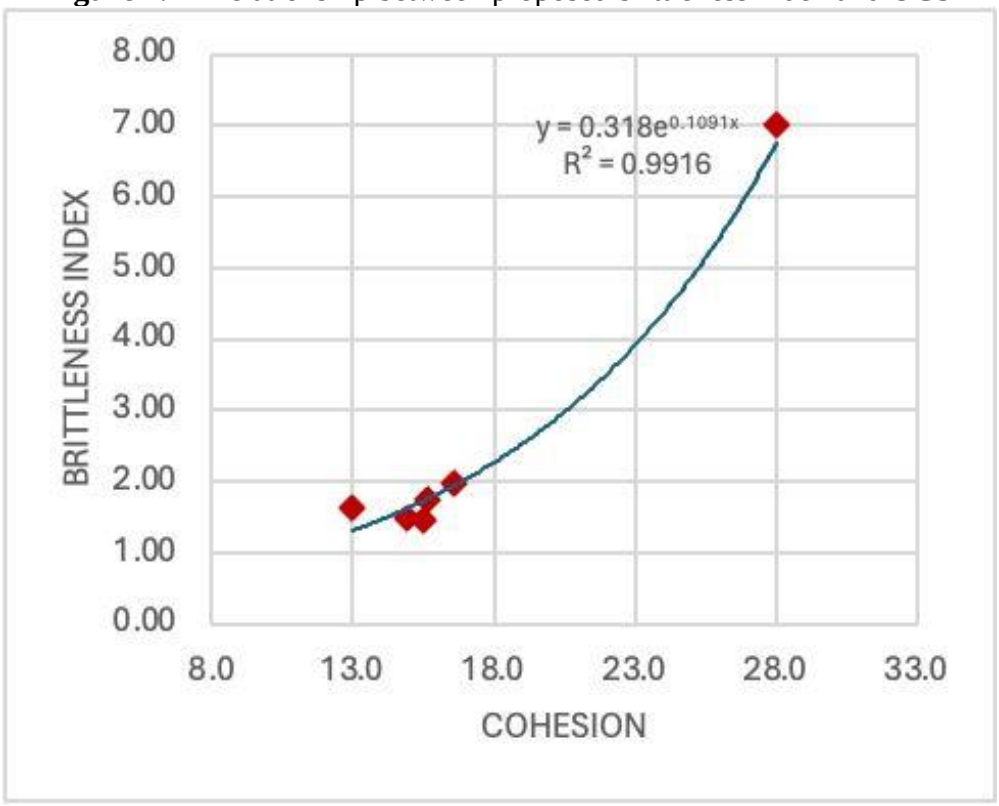


**Figure 4.15** Relationship between proposed brittleness index and cohesion

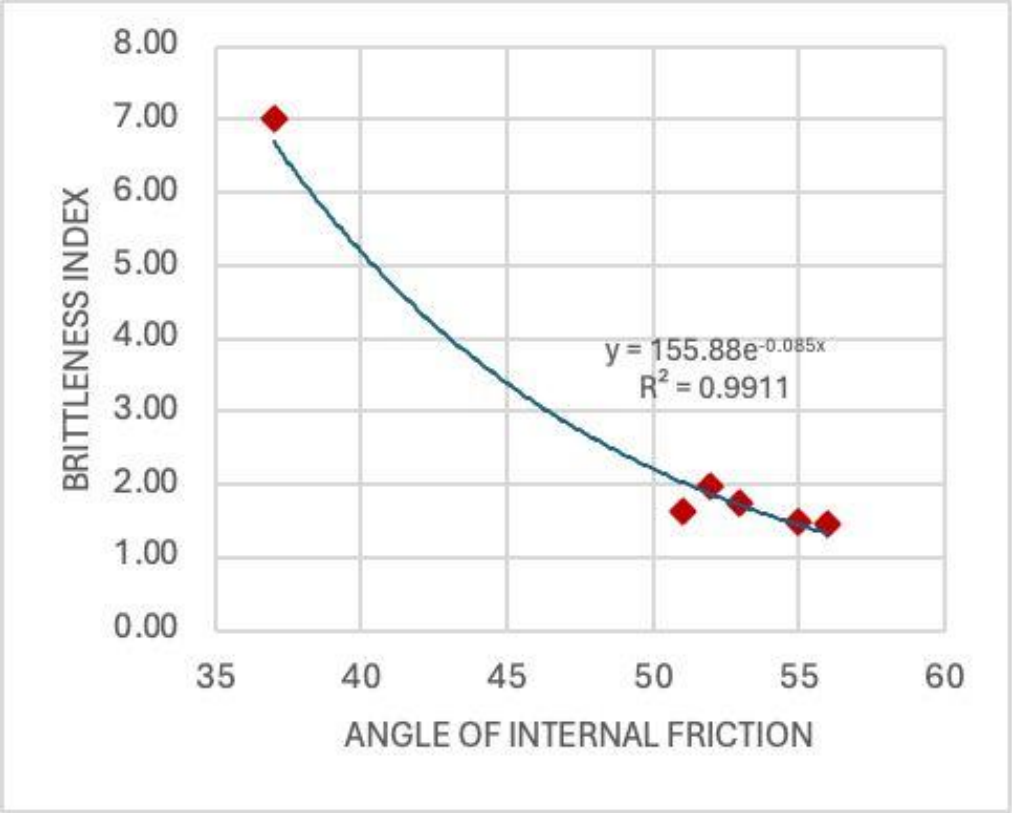


**Figure 4.16** Relationship between proposed brittleness index and angle of internal friction

The brittleness index has values of 1.62 at room temperature and 7 at 200°C as shown in figure 4.16, and thereafter values gradually decreased with temperature. The lowest value of the index was 1.44 at 600°C. That means that the index first increased and then decreased with increasing temperature. The identical behaviour was shown by UCS as well as cohesion with respect to temperature. Relationship between proposed brittleness index and angle of internal friction is shown in figure 4.15.

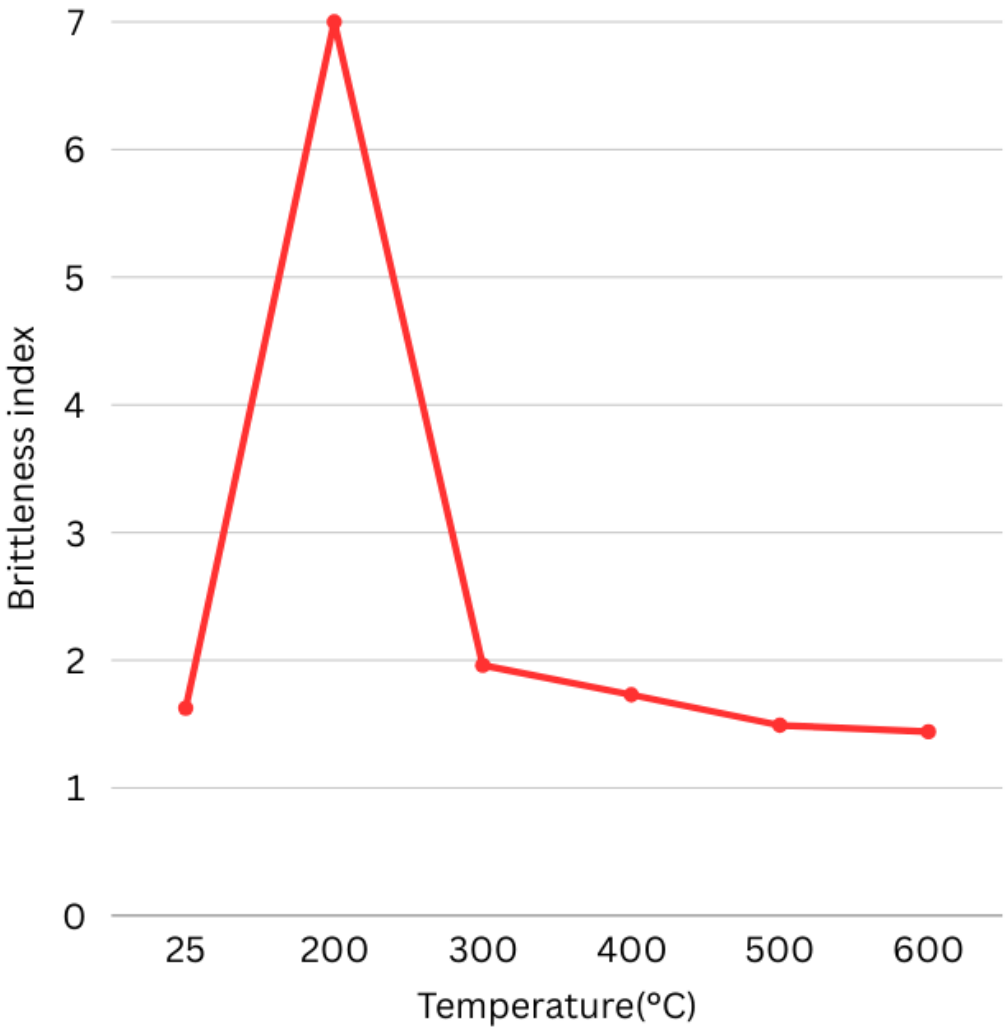


**Figure 4.17** Relationship between proposed brittleness index and temperature

The proposed brittleness index is based solely on cohesion and angle of internal friction. Higher the value of the brittleness index more would be the brittleness of the rock. The index value first increased and then decreased with temperature as shown in figure 4.16. The index developed derives inspiration from Mohr coulomb's failure criteria's equation based on principal stresses and cohesion and angle of internal friction. The equation was helpful in expressing strength in relationship with cohesion and angle of internal friction.

# CHAPTER 5
# CONCLUSION AND FUTURE WORK

## 5.1 Conclusion

Following the literature review, different tests were performed on sandstone samples, they were subjected to different temperatures so that the effect of temperature on its properties can be understood. After all these events the following can be concluded:

1)Brittleness is an important mechanical property of sandstone. It has applications in different fields of engineering like mining. Brittleness is expressed quantitatively with the help of brittleness Index. It is based on different parameters like uniaxial compressive strength and tensile strength etc. There are many factors affecting brittleness of sandstone like temperature, porosity, texture, total organic content etc.

2)The Chunar sandstone has silica as the most dominant mineral followed by aluminium oxide and potassium oxide and other minerals in traces. The porosity of sandstone was found to increase with increase in temperature. The density was found to decrease with increasing temperature. The density was constant between 200-300°C and thereafter decreased. The Vp and Vs were found to continuously decrease with increasing temperature. This indicates the continuous development of micro cracks and evaporation of water within the rock matrix. The wave propagation is negatively affected due to progressive disappearance of continuity of material.

3)The UCS was found to increase till 200°C thereafter decrease which was due to formation of microcracks and trapping up of particles within these cracks because of ablation which in turn supports its ability to handle more load the Brazilian tensile strength was found to increase till 400°C and thereafter decrease. The fall in strength between 400-600°C was because of evaporation of water within the pores in rock matrix. The value of Cohesion was found to be matching to the pattern of that of UCS. The angle of internal friction followed the opposite trend to that of cohesion..

4)A new brittleness index was proposed based on cohesion and angle of internal friction. The proposed index has good correlations with brittleness index $B_1$,$B_2$,$B_3$,UCS,cohesion and φ. The value of $R^2$ was 0.91,0.91,0.91 for $B_1$, $B_2$, $B_3$ and 0.92,0.99,0.99 for UCS, cohesion and angle of

internal friction respectively. The index first increases till 200°C and thereafter decreases with increasing temperature. Higher the value of the Index more would be the brittleness of the rock.

## 5.2 Future Work

The future work can be as follows

1. Development of range of values of brittleness index with associated remarks. For example, a scaling system so that one can discern from values of brittleness index whether brittleness is high or low.
2. Testing the applicability of index in different fields of engineering.

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